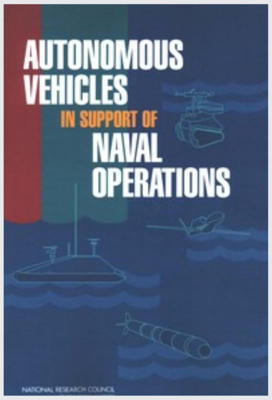

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CONTRIBUTORS

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AUTONOMOUS VEHICLES IN SUPPORT OF NAVAL OPERATIONS

Committee on Autonomous Vehicles in Support of Naval Operations

Naval Studies Board

Division on Engineering and Physical Sciences

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Preface

Recent naval operations in Kosovo, Afghanistan, and Iraq have been carried out successfully in a joint environment in which much useful information was generated by unmanned aerial vehicles. These experiences have sharpened insight into the nature of complex threats and how to deal with them in order to assure access for maneuver and the delivery of effective firepower. Furthermore, foreign ports and the homeland must be defended against threats—some "asymmetric" and some sophisticated—which may arrive by sea or air. These threats are often characterized by their mobility and may be attempted over extended periods of time. Surveillance must thus take place over wide areas and operate over long time periods, which can be risky and at least wearing for the personnel involved. The possible costs and risks incurred are strong arguments for expanded use of unmanned vehicles in future operations.

The successful use of unmanned vehicles in recent operations has led to recognition of their broader utility and to additional calls for more unmanned vehicles by President George W. Bush and his Secretary of Defense, Donald H. Rumsfeld. Attracted by the prospect of lower unit cost and risk for unmanned vehicles than for manned vehicles, all of the Services have been active in this area with initiatives and plans for unmanned aerial vehicles (UAVs), uninhabited combat air vehicles (UCAVs), unmanned ground vehicles (UGVs), unmanned surface vehicles (USVs), and unmanned undersea vehicles (UUVs); in some cases there have been operational deployments. From these efforts it has become widely appreciated that unmanned vehicle systems can offer many opportunities, including surveillance and reconnaissance, targeting of firepower with onboard weapons, damage assessment, and service as communications nodes and for signals intelligence, environmental measurements, and the detection and identification of nuclear, biological, and chemical threats.

Recent experiments and evaluations have indicated that before the effective deployment of unmanned vehicles, many technical and operational questions remain to be addressed, such as the level of autonomy needed, as well as issues relating to reliability, environmental sensitivity, vehicle integration, and operational training. The technical challenges include size, endurance, speed, recoverability, survivability, altitude or depth range, along with onboard and offboard trade-offs related to communications, intelligence, situation awareness (for deconfliction), replanning capability (needed for threat changes), multiple vehicle control, and human interfaces. The topic of autonomous vehicles clearly has many aspects and corresponding technological challenges that must be addressed in order to enhance their overall utility to naval (and joint) operations.

In August 2002, the Chief of Naval Operations requested that the National Research Council, under the auspices of the Naval Studies Board, establish a committee to review the status of, experience with, technology challenges related to, and plans for development and concepts for autonomous vehicles (AVs) in support of naval operations. The terms of reference for the study are provided below. John J. Deyst of the Massachusetts Institute of Technology chaired the committee. Biographical information on the membership and staff is presented in Appendix A.

TERMS OF REFERENCE

At the request of the Chief of Naval Operations, the Naval Studies Board of the National Research Council conducted a study across all naval operational environments—sea, air, land, and space—to address the following (the chapters of the report that address each issue are shown in brackets):

- Review the status, experience, and lessons learned to date with autonomous vehicles in the military and other functional areas (space, industry, energy) [Chapters 1 and 3];
- Identify capabilities needed to improve the utility of autonomous vehicles in military operations and homeland defense, taking into account projected threats [Chapter 2];
- Examine and project technologies needed to achieve these capabilities, and the levels of autonomy involved [Chapters 3 through 6];
- Investigate the functional utility between vehicle autonomy and overall system complexity, survivability, and safety, accounting for networking, systems integration, logistics, and training [Chapter 3];
- Evaluate the potential of synergies involving combinations of autonomous vehicles and other naval platforms in military operations and homeland defense [Chapter 7]; and

• Identify opportunities and means for transitioning autonomous vehicles in support of naval operations, including systems integration issues related to battle group and amphibious readiness group compatibility [Chapters 4 through 6].

COMMITTEE MEETINGS

The Committee on Autonomous Vehicles in Support of Naval Operations first convened in December 2002 and held further meetings and site visits over a period of six months, as summarized in the following list.

• *December 9-10, 2002, in Washington, D.C. (Plenary Session).* Organizational meeting. Office of the Chief of Naval Operations (OPNAV), N81 and N513G, overview of Sea Power 21 and the vision of the future Navy; OPNAV, N780X, overview of Navy unmanned aerial vehicle requirements and initiatives; Defense Advanced Research Projects Agency (DARPA) briefing on DARPA science and technology initiatives on unmanned vehicles; U.S. Navy Program Executive Office, Littoral and Mine Warfare briefing on Navy unmanned undersea, sea surface, and ground vehicle technology development and transition; U.S. Navy Program Executive Office, Strike Weapons and Unmanned Aviation briefing on Navy unmanned aerial vehicle technology development and transition; Marine Corps Warfighting Laboratory briefing on Expeditionary Maneuver Warfare, vision of the future Marine Corps, and Marine Corps perspective on requirements and initiatives for unmanned vehicles; Office of the Secretary of Defense (OSD) Joint Robotics Program briefing on initiatives on unmanned ground vehicles; Naval Research Advisory Committee (NRAC) briefing on NRAC study on the role of unmanned vehicles; Office of Naval Research (ONR) and Naval Air Systems Command briefings on the autonomous operations Future Naval Capability program; and OSD overview of OSD Roadmap on Unmanned Aerial Vehicles.

• *January 25-26, 2003, in Washington, D.C.* Naval Surface Warfare Center, Dahlgren Division study outbrief on shaping the future of naval warfare with unmanned systems; OPNAV, N61, overview of FORCEnet and the role unmanned vehicles play; OPNAV, N2, overview of Navy intelligence, surveillance, and reconnaissance (ISR) capabilities and the role unmanned vehicles play; National Imagery and Mapping Agency overview of Digital Point Positional Database; OPNAV, N70, briefing on Navy requirements for unmanned vehicles; Northrop Grumman Corporation briefing on Global Hawk performance in Operation Enduring Freedom; Headquarters Marine Corps overview of Marine Corps ISR capabilities and the role unmanned vehicles play; Marine Corps Combat Development Command briefing on Marine Corps requirements for unmanned vehicles; and U.S. Navy Program Executive Office, Littoral and Mine Warfare briefing overview of Navy Unmanned Underwater Vehicle Master Plan.

- *February 25-26, 2003, in Washington, D.C.* OPNAV, N763, briefing on Navy unmanned surface vehicle requirements and an overview of the Littoral Combat Ship; Naval Surface Warfare Center, Carderock Division (NSWC/CD), briefing on NSWC/CD autonomy and unmanned vehicle initiatives; U.S. Coast Guard Program Executive Office, Integrated Deepwater Program, briefing on the role of unmanned vehicles in homeland security; Office of the Assistant Secretary of Defense, Command, Control, Communications, and Intelligence (OASD C3I) briefing on the Global Information Grid, Transformational Communications, and other OSD efforts related to autonomous, unmanned vehicles; U.S. Air Force Office of the Deputy Chief of Staff for Air and Space Operations briefing on Air Force Predator performance in Operation Enduring Freedom; ONR, Code 321, briefing on ONR autonomy and unmanned vehicle initiatives; Naval Undersea Warfare Center (NUWC) briefing on NUWC autonomy and unmanned vehicle systems; and Navy Warfare Development Command (NWDC) briefing on NWDC autonomy and unmanned vehicle experimentation and concept development.
- *March 25-27, 2003, in San Diego, California.* Briefings from AAI Corporation, Frontier Systems, AeroVironment, Boeing, Lockheed Martin, Raytheon, Monterey Bay Aquarium Research Institute, and Jet Propulsion Laboratory on technical background of their respective autonomous, unmanned vehicle programs; site visits to Naval Air Force, U.S. Pacific Fleet, for briefing on Naval Air Force operational perspectives on autonomous unmanned vehicles; Naval Surface Force, U.S. Pacific Fleet, briefing on Naval Special Force operation perspectives on autonomous unmanned vehicles; Naval Special Warfare Command briefing on operational and technical perspectives for employing autonomous, unmanned vehicles; U.S. Third Fleet briefings on operational and technical perspectives for employing autonomous, unmanned vehicles and operational use of Naval Fires Network; Northrop Grumman briefings on unmanned systems initiatives at Northrop Grumman; Space and Naval Warfare Systems Command (SPAWAR) briefings on undersea warfare FORCEnet concept, C4ISR (command, control, communications, computers, intelligence, surveillance, and reconnaissance) for UAVs, UGVs, UUVs, very shallow water programs, chemical sensing in the marine environment and adaptive mission planning, Slocum undersea gliders, communications for unmanned vehicles, and expeditionary pervasive sensing enabling experiments; Program Executive Office for Command, Control, Communications, Computers, and Intelligence and Space (PEO C4I) overview of acquisition initiatives related to autonomous, unmanned vehicles; Jet Propulsion Laboratory on machine vision; and General Atomics Aeronautical Systems discussion on unmanned vehicle programs and initiatives.
- *April 25-26, 2003, in Washington, D.C.* Naval Air Systems Command (NAVAIR) briefing on uninhabited combat air vehicle-Navy (UCAV-N) carrier operation and the status of improving the reliability of automated carrier landing systems; Naval Research Laboratory (NRL) briefing on tactical microsatellites, sensors, autonomy, and other related AV developments; ONR briefing on the

Navy's Autonomous Intelligent Network and Systems (AINS) initiative and other science and technology (S&T) initiatives; DARPA briefing on autonomous space tactical operations, unmanned ground systems, and other DARPA S&T initiatives; DRS Technologies briefing on Neptune Maritime UAV and other related developments; NAVAIR, PMA 263, briefing on status of and initiatives in the Navy unmanned aerial vehicles program and status of improving the reliability of automated carrier landing system for UCAV-N (and other UAV initiatives); Carnegie Mellon University briefing on autonomous and teleoperated field robotics; and Office of the Assistant Secretary of the Army (Acquisition, Logistics, and Technology) briefing on the U.S. Army's Objective Force Vision, Future Combat Systems, and the role unmanned vehicles play.

- *May 19-23, 2003, in Irvine, California (Plenary Session).* Committee deliberations and report drafting.

The months between the last committee meeting and publication of this report were spent preparing the draft manuscript, gathering additional information, reviewing and responding to external review comments, editing the report, and conducting the required security review to produce a public report.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Charles H. Bennett, IBM Thomas J. Watson Research Center,
Ray "M" Franklin, Major General, U.S. Marine Corps (retired), Port Angeles, Washington,
David E. Frost, Vice Admiral, U.S. Navy (retired), Frost & Associates, Inc.,
Takeo Kanade, Carnegie Mellon University,
Clinton W. Kelly, Science Applications International Corporation,
Larry Matthies, Jet Propulsion Laboratory,
Irene C. Peden, Seattle, Washington, and
Dana R. Yoerger, Woods Hole Oceanographic Institution.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions and recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Lee M. Hunt, Alexandria, Virginia. Appointed by

the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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AUTONOMOUS VEHICLES IN SUPPORT OF NAVAL OPERATIONS

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SIGNIFICANT FINDINGS

Autonomous vehicles (AVs) have been used in military operations for more than 60 years, with torpedoes, cruise missiles, satellites, and target drones being early examples.[1] They have also been widely used in the civilian sector—for example, in the disposal of explosives, for work and measurement in radioactive environments, by various offshore industries for both creating and maintaining undersea facilities, for atmospheric and undersea research, and by industry in automated and robotic manufacturing.

Recent military experiences with AVs have consistently demonstrated their value in a wide range of missions, and anticipated developments of AVs hold promise for increasingly significant roles in future naval operations. Advances in AV capabilities are enabled (and limited) by progress in the technologies of computing and robotics, navigation, communications and networking, power sources and propulsion, and materials.

As a result of its deliberations, the Committee on Autonomous Vehicles in Support of Naval Operations developed a number of findings. Among the most

[1]In defining "autonomous vehicles" for purposes of this study, the Committee on Autonomous Vehicles in Support of Naval Operations elected to include all vehicles that do not have a human onboard. This definition is broad enough to include weapons systems such as torpedoes, mobile mines, and ballistic and cruise missiles—although these systems are not discussed in this report. Space vehicles are also not discussed, although the applications of space such as enhanced command, control, and communications (C3) are discussed for their role in enabling autonomous vehicles.

significant of the findings is the recognition that many naval requirements can be fulfilled, at least in part, by AV systems already in the inventory or under development by other Services. Hence, the U.S. Navy and the U.S. Marine Corps should collaborate with other Services to take maximum advantage of both operational systems and systems in various stages of development. Also, the Naval Services should form an effective partnership between the operational and the technology development and production communities and develop an effective process for embracing joint and commercial programs in order to aggressively exploit existing autonomous systems and new technologies.

The committee finds that it is important to put existing AV systems in operational situations in order to give personnel experience with the systems' capabilities, and then to develop requirements based on this experience. **In particular, since the operational utility and military worth of unmanned aerial vehicles (UAVs) have been demonstrated in recent military operations, it is essential that the Naval Services accelerate the introduction and/or fully exploit the capabilities of those UAV systems, from all of the military Services, that are now in production, or that have completed development.**

It is also evident that there are some unique requirements for which the Naval Services must develop technologies that are not being pursued by other Services or by the civilian sector. **Thus, it is important for the Navy to pursue the development of critical autonomous vehicle-related technologies considered essential to the accomplishment of future naval missions. The progress of these developments needs to be tracked year to year.**

In its deliberations, the committee also found significant deficiencies in command, control, communications, computers, intelligence, surveillance, and reconnaissance (C4ISR) that now limit the utility of AVs. **Therefore, it is essential that the Department of the Navy formulate and execute a comprehensive plan to eliminate these C4ISR deficiencies.**

A final significant finding is that an AV's level of autonomy is an important system variable that should be included, from the outset, in the development of AV systems. **Hence it is important for the Department of the Navy to mandate that the level of autonomy be stipulated as a required design trade-off in autonomous vehicle development contracts.**

The following sections elaborate on these significant findings and provide the committee's detailed recommendations.

ACCELERATE THE INTRODUCTION OF EXISTING AUTONOMOUS VEHICLES

Operational experience with current autonomous vehicles—especially with such UAVs as the Predator, Global Hawk, and special-purpose systems used during recent conflicts—has demonstrated that, once they are employed by warfighters, the value of AVs becomes immediately evident and strong advocacy begins to build. Hence, an important strategy to increase involvement of the Naval Services with AVs is to accelerate the introduction or exploitation of those systems that are in production, or in the later stages of development, and judged to have significant operational utility for naval missions.

The Navy views its future use of unmanned aerial vehicles to be primarily in three categories:

- Long-dwell, standoff intelligence, surveillance, and reconnaissance (ISR), as exemplified by the Broad Area Maritime Surveillance (BAMS) concept and the Global Hawk Maritime Demonstration (GHMD);
- Carrier-based, penetrating surveillance and suppression of enemy air defense (SEAD)/strike Joint Unmanned Combat Air System (J-UCAS); and
- Ship-based tactical surveillance and targeting, which call for a vertical-takeoff-and-landing (VTOL) system that can operate from a variety of ship types.

In reviewing the Navy's progress toward realizing this three-category future, with respect to UAVs, the committee noted that the Advanced Technology Demonstration (ATD) for the Defense Advanced Research Projects Agency (DARPA)/ Uninhabited Combat Air Vehicle-Navy (UCAV-N) program has transitioned into a combined effort with the Air Force along the lines of the Joint Strike Fighter program.

The road ahead seems unclear for the long-dwell, standoff ISR system. The committee noted the near-concurrency of the GHMD and contract award for the BAMS UAV, and thus it remains concerned that lessons from the Global Hawk demonstration might not be reflected in the BAMS program.

At present the Navy has no capability for ship-based tactical unmanned aerial vehicles (TUAVs) and organic ISR. There are, however, plans that link the Fire Scout vertical-takeoff-and-landing TUAV (the VTUAV) with the nascent Littoral Combat Ship (LCS) as the latter begins to enter operational service after 2007. Here the committee is concerned that the introduction of a sea-based tactical surveillance and targeting capability in the fleet, which could begin with the Fire Scout as early as 2005, now appears to be tied to the development of a new ship class not scheduled for initial operating capability until after 2007.

The Marine Corps envisions three levels of UAV support for its warfighters operating from the sea or ashore in Marine Air Ground Task Forces (MAGTFs). At the theater level, the MAGTFs will rely on national systems as well as on information derived from the Global Hawk and Predator. At the tactical level, the Marine Corps plan is for MAGTFs to continue relying on the Pioneer for operations ashore until it is replaced by a TUAV system suitable for use from both sea and land bases. At the lower tactical unit level, the Marine Corps's TUAV need is to be satisfied by the human-portable Dragon Eye UAV system.

The committee believes that ship-capable tactical unmanned aerial vehicles need to be introduced into the Naval Services without further delay—and since the Fire Scout is the only such system currently available, the Navy can move immediately to acquire a small force of Fire Scouts to develop operational concepts and tactics. Further, to facilitate an accelerated introduction of the Fire Scout into the fleet in 2005, a VTUAV tactical development squadron should be formed by the Navy and the Marine Corps, and the Coast Guard invited to participate. Since the Army has selected the Fire Scout for its Future Combat System (FCS), the Army needs to be invited to participate as well.

Finally, the committee concludes that the Naval Services should begin the selection of a growth VTUAV capability, which may include a tilt-rotor variant, or other suitable VTOL systems under development by DARPA (e.g., A-160 Hummingbird, unmanned combat armed rotorcraft, or X-50 Dragonfly canard rotor wing), as the principal, sea-based TUAV of the future.

Recommendation 1: The Navy and Marine Corps should aggressively exploit the considerable warfighting benefits offered by autonomous vehicles (AVs) by acquiring operational experience with current systems and using lessons learned from that experience to develop future AV technologies, operational requirements, and systems concepts. Specifically:

1.1 Accelerate the Introduction of Unmanned Aerial Vehicles. The Navy and Marine Corps should accelerate the introduction, or fully exploit the capabilities, of those unmanned aerial vehicle (UAV) systems of all of the military Services that are now in production or through development and judged to have significant operational utility, such as the Global Hawk, Predator, Shadow 200, Fire Scout, and Dragon Eye. Concurrently, the two Services should move vigorously to eliminate or significantly mitigate deficiencies in the equipment and infrastructure of command, control, and communications (C3) and imagery-exploitation systems that limit the use of the aforementioned UAV systems. It is important for the naval operational community to develop the operational concepts and create the operational pull necessary to accelerate UAV introduction.

1.2 Accelerate the Introduction of Unmanned Undersea Vehicles. The Chief of Naval Operations (CNO) should direct the Commander, Fleet Forces Command, to deploy and evaluate systems such as the Long-Range Mine Reconnaissance System, the Remote Minehunting System, and the Remote Environmental Monitoring Unit System in order to refine concepts of operations, cost issues, logistics, and handling.

1.3 Accelerate the Introduction of Unmanned Ground Vehicles. The Office of Naval Research should support continued research into the use of unmanned ground vehicles (UGVs) as a potential solution to the mapping and clearance of surf zone and beach mines, and into UGV alternatives to unmanned aerial vehicles for surveillance missions in support of shore bombardment. Testing and development of the Gladiator and Dragon Runner should be increased in order to refine the capabilities of both systems. Partnering by the Navy and Marine Corps with the U.S. Army's Future Combat System program in research and development efforts to develop UGV components should be encouraged by the Navy and Marine Corps.

1.4 Develop a Long-Dwell, Standoff Intelligence, Surveillance, and Reconnaissance Unmanned Aerial Vehicle System. The Navy should aggressively pursue the development and fielding of a long-dwell, standoff intelligence, surveillance, and reconnaissance (ISR) UAV system along the general lines of the Broad Area Maritime Surveillance (BAMS) concept and formally join the Navy with the Air Force to develop, procure, and operate a common high-altitude, long-endurance UAV system suitable for both overland ISR and BAMS maritime missions. In their joint approach, the two Services should increase the system production rate above that now planned in order to realize operational and cost benefits. They should also explore the potential for a joint arrangement with the Department of Homeland Security and its agencies. The current EA-6B (Prowler aircraft) program should be considered as an initial Memorandum of Agreement model.

1.5 Evaluate a Vertical-Takeoff-and-Landing Tactical Unmanned Aerial Vehicle (VTUAV) System on an Accelerated Basis. The Assistant Secretary of the Navy (Research, Development, and Acquisition) should support a limited procurement of Fire Scout systems to provide the fleet in the near term with a modern, automated, ship-based, vertical-takeoff-and-landing UAV for developing operational concepts and requirements for a future naval VTUAV system and to serve as a contingency response resource. To facilitate the accelerated introduction of the Fire Scout into the fleet in 2005, a VTUAV tactical development squadron should be formed by the Navy and the Marine Corps, and the Coast Guard should be invited to participate. Since the Army has selected the Fire Scout for its Future Combat System, the Army should be invited to participate as well.

1.6 Develop Future Sea-Based Tactical Unmanned Aerial Vehicle Requirements. The Navy and Marine Corps should jointly develop requirements for a future sea-based tactical UAV system that will meet the needs of the Marine Corps's Ship-to-Objective Maneuver concept afloat and ashore and is suitable for employment on a variety of ship types—the Littoral Combat Ship (LCS) and future destroyer (DD(X)) as well as current surface combatants and amphibious ships. The requirements should reflect lessons gleaned from future Fire Scout operations as well as developments of the Coast Guard's Eagle Eye, the Defense Advanced Research Projects Agency/Army A-160 long-endurance helicopter, and other advanced vertical-takeoff-and-landing concepts. In addition, those requirements should flow down to address the maintenance concepts and logistics needs of UAVs, as well as those of other unmanned systems, onboard various future ship types, including the LCS, DD(X), amphibious ships, and the ships of the Maritime Prepositioning Force (Future), which will form the core of the new Sea Basing concept.

1.7 Revisit and Strengthen the Unmanned Aerial Vehicle (UAV) Roadmap. The CNO and the Commandant of the Marine Corps (CMC) should assign responsibility for the review and revision of the naval UAV Roadmap to establish a clear plan to address advanced technology needs and the timely introduction of new UAV capabilities and to resolve tactical UAV issues between the two Services.

1.8 Establish a Joint Services Unmanned Aerial Vehicle Forum. The CNO and the CMC should together recommend to the Commander, Joint Forces Command, that a joint-Services annual forum be established. The forum should encourage interaction between UAV developers and operators of all of the military Services, resolve interoperability issues, and identify new warfighting capabilities for UAVs that may be applicable in urban and littoral warfare environments. A key task should be pinpointing missions that might be executed more effectively and economically by UAVs and formulating system requirements to meet those needs. Where appropriate, and in situations in which needs cannot be met by other means, the forum should recommend what new UAV developments need to be initiated. The forum should also foster experimentation and should formulate and recommend operational and technical experiments involving UAV systems, including collaborations of UAVs with manned vehicles.

1.9 Foster Flight of Unmanned Aerial Vehicles in Controlled Airspace. In concert with the other military Services, the Secretary of the Navy should work to ensure that the Department of Defense is actively supporting initiatives that will lead to safe, unrestricted flight by UAVs in the U.S. National Airspace System, in international controlled airspace, and in combat theaters.

PURSUE NEW AUTONOMOUS VEHICLE CONCEPTS AND TECHNOLOGIES

The Office of Naval Research's (ONR's) Autonomous Operations Future Naval Capability[2] (FNC) has initiated a four-pronged autonomy technology development effort. This effort, in concert with the Department of Defense's (DOD's) autonomy technology portfolio and ongoing DOD programs, provides a pipeline of maturing technologies that can be used to create, in the near term, new Navy and Marine Corps autonomous vehicle capabilities.

Despite the autonomy capabilities that can now be leveraged from the DOD's portfolio or that are currently being developed via ONR's Autonomous Operations FNC, much remains to be done if the Navy's future vision is to be fully realized. The focus of future Naval Services' investments and the pace of autonomy technology development needs to be carefully mapped, with cognizance of work being done across the DOD.

Recommendation 2: The Assistant Secretary of the Navy for Research, Development, and Acquisition (ASN(RD&A)) and the Chief of Naval Research (CNR) should direct the Navy and Marine Corps Systems Commands, the Office of Naval Research (ONR), and the Marine Corps Warfighting Laboratory (MCWL) to partner with the operational community and monitor the concepts and development of critical autonomous vehicle-related technologies considered essential to the accomplishment of future naval missions. The progress of these developments should be tracked year to year. Specifically:

2.1 Pursue New Autonomy Concepts and Technology Developments. The ASN(RD&A) should direct appropriate agencies in the Navy and Marine Corps to formulate and maintain a list of the most promising moderately to highly mature autonomy technologies (Technology Readiness Level > 4) that can enable critical near-term autonomous vehicle capabilities. Plans to pursue further development of these capabilities should be developed and funded, and progress should be tracked year to year to ensure the proper pace of development.

The ONR should develop autonomous vehicle research and development (R&D) needs and a technology roadmap to achieve the goals defined by the various vision documents of the Naval Services. ONR should leverage the current operational experience and the recommended increase in future operational

[2] In 1999, the Department of the Navy adopted a new process for concentrating its scientific and technological resources to achieve Future Naval Capabilities (FNCs). Since then, much of the nearer-term applied science and technology effort of the Navy and Marine Corps has been devoted to providing the means to achieve these capabilities.

experience with autonomous vehicles in order to define R&D needs to address specific, high-value operational needs.

2.2 Pursue New Unmanned Aerial Vehicle Concepts and Technology Developments. The ASN(RD&A) should ensure that the respective Services monitor promising new unmanned aerial vehicle (UAV) concepts and developments, including the Defense Advanced Research Projects Agency (DARPA)/Air Force/Navy Joint Unmanned Combat Air System (J-UCAS), the A-160 Hummingbird, Eagle Eye, X-50 Dragonfly canard rotor wing, unmanned combat armed rotorcraft, organic aerial vehicles, and micro-UAVs. Particular attention should be paid to the DARPA/Army/Special Operations Command A-160 long-endurance rotorcraft program and the Coast Guard's Eagle Eye tilt-rotor development, since these systems offer promise as potential long-dwell intelligence, surveillance, and reconnaissance (ISR) and short-range tactical UAVs, respectively, as well as the DARPA/Air Force/Navy J-UCAS Advanced Technology Demonstration that is developing a stealthy, long-endurance, carrier-based, unmanned combat armed rotorcraft suitable for ISR, suppression of enemy air defense, and strike missions.

The ASN(RD&A) and the CNR should ensure that the Naval Air Systems Command, ONR, and MCWL, in coordination with the Army, Air Force, and DARPA, monitor the need for, progress, and development of technologies that would help realize more effective UAV systems to accomplish future naval missions. At a minimum, the following technologies should be considered in this context:

- Dependable and secure communications, including bandwidth and latency;
- Positive automatic target-recognition and image-processing software;
- Automated contingency planning;
- Intelligent autonomy;
- Systems-oriented flight operations;
- Autoland systems;
- Fuel-efficient, small-turbine, and heavy-fuel internal combustion engines; and
- Survivability features.

In addition, a number of advanced UAV concepts should be continually evaluated, including the following:

- Operations in dirty environments;
- Autonomous aerial refueling;

- J-UCAS for Combat Air Patrol, Airborne Early Warning, and Close Air Support;
- Very small UAVs;
- Deployment of ground sensors from UAVs;
- Aerial release and redocking of UAVs;
- Extreme-endurance systems;
- Advanced sensor combined with UAVs; and
- Optionally piloted air vehicles.

2.3 Pursue New Unmanned Surface Vehicle/Unmanned Undersea Vehicle Concepts and Technology Developments. The Chief of Naval Operations should establish a high-level working group to refine the requirements and concepts of operations for unmanned surface vehicles and other autonomous vehicles as an integral part of the Littoral Combat Ship (LCS) and other naval operations. Once the LCS design is completed, planning for logistical support, maintenance and handling space, and launch-and-recovery systems for autonomous vehicles should be incorporated.

The ASN(RD&A) and the CNR should direct the ONR to monitor commercial developments in unmanned surface vehicle (USV)/unmanned undersea vehicle (UUV) technologies and to take maximum advantage of those developments for meeting the Navy's needs. Specifically, the ASN(RD&A) and the CNR should direct the ONR to invest in and develop networks of small UUVs. These efforts should include the leveraging of research and experimentation within the oceanographic research and oil exploration communities.

The ASN(RD&A) and the CNR should direct the ONR to conduct research into adaptive and cooperative autonomy and communications. ONR should develop better energy sources, as well as launch-and-recovery systems and environmental sensors for UUVs and USVs. Increased investment is needed in basic research and development in the areas of acoustics and optics as well as in sensors for mine hunting, including synthetic aperture sonar. ONR and the Naval Air Systems Command should focus on the modularity of components (propulsion, energy, and sensors), common architectures, common mission planning, and common integration pathways for data. The ASN(RD&A) and the CNR should ensure that UUVs and USVs, whenever possible, meet the interoperability and communications requirements of the Department of the Navy's FORCEnet operational concept.

2.4 Pursue New Concepts and Technology Developments for Unmanned Ground Vehicles. The ONR should pursue a broad spectrum of R&D on unmanned ground vehicles (UGVs) themselves and on their components. The R&D should range from basic research in sensors and sensor processing to field tests of complete systems. The Navy should continue to partner with the Office of the

Secretary of Defense, DARPA, and the Army, as appropriate, utilizing the capabilities of the Space and Naval Warfare Systems Command for these activities.

INTEGRATE AUTONOMY IN NETWORK-CENTRIC OPERATIONS

To realize network-centric operations,[3] it is necessary for the Navy to develop an adequately funded FORCEnet[4] implementation plan and management structure to coordinate with the Office of the Secretary of Defense and other Services with respect to requirements and interoperability; to support the Office of the Secretary of Defense (Networks and Information Integration) in its Transformational Communications efforts; to conduct the necessary systems engineering, to assign requirements to Navy platforms, and to provide funding for satisfying these requirements.

The committee finds that to facilitate the exploitation of UAV data, it is necessary to develop a robust, joint, network-centric "task, process, exploit, disseminate/task, post, process, use" (TPED/TPPU) environment, employing standard data formats for ISR products to permit networked exploitation. Research needs to be focused on the development of automated tools for tracking, fusion, automatic target recognition, and sensor management.

The committee finds that the achievement of the Naval Services' future vision requires the standardization of interfaces, protocols, and the development of common architectures for autonomous vehicle communications and control. Also, the current challenges in the exploitation of autonomous vehicle ISR information, coupled with the expected future explosion in the generation of ISR information by autonomous vehicles, require the development of a new approach to mitigate ISR analyst saturation.

The Department of the Navy needs to expand its initial interaction and involvement in the Space Based Radar program. To enhance its capabilities for Broad Area Maritime Surveillance, the Navy needs to negotiate a Memorandum of Agreement with the Air Force to integrate ocean surveillance modes into the space-based radar (SBR). In this context, the Navy could develop and exercise connectivity and systems to exploit SBR surveillance data and to plan and control SBR maritime surveillance missions, and it could work with unified combatant commanders to develop plans and procedures for obtaining access to SBR resources when required.

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[3]National Research Council. 2000. *Network-Centric Naval Forces: A Transition Strategy for Enhancing Operational Capabilities*, National Academy Press, Washington, D.C.

[4]FORCEnet is the "operational construct and architectural framework for naval warfare in the information age, integrating warriors, sensors, command and control, platforms, and weapons into a networked, distributed combat force." Source: ADM Vern Clark, USN. 2002. "Sea Power 21: Projecting Decisive Joint Capabilities," *U.S. Naval Institute Proceedings*, Vol. 128, No. 10, pp. 32-41.

Recommendation 3: The Assistant Secretary of the Navy for Research, Development, and Acquisition (ASN(RD&A)) should formulate and execute a comprehensive plan to eliminate or significantly mitigate deficiencies in command, control, communications, computers, intelligence, surveillance, and reconnaissance systems equipment and infrastructure, including communications bandwidth, that now limit the use of modern intelligence, surveillance, and reconnaissance (ISR) systems for autonomous vehicles. Specifically:

3.1 Develop an Adequately Funded FORCEnet Implementation Plan. The Chief of Naval Operations (CNO) and the Commandant of the Marine Corps (CMC) should coordinate an adequately funded FORCEnet implementation plan and management structure to interact with the Office of the Secretary of Defense and other Services on the requirements and interoperability necessary to support network-centric operations.

3.2 Facilitate Exploitation of Unmanned Aerial Vehicle Data. The CNO and the CMC should take measures to facilitate the exploitation of unmanned aerial vehicle (UAV) data by developing a robust, joint, network-centric "task, process, exploit, disseminate/task, post, process, use" (TPED/TPPU) environment, utilizing standard data formats for ISR products to permit distributed exploitation. Automatic target recognition-like techniques should be explored so as to more rapidly screen large volumes of electro-optical/infrared and synthetic aperture radar imagery generated by ISR UAV systems such as the Global Hawk. The Naval Network Warfare Command and the Space and Naval Warfare Systems Command should implement an organizational structure and a systems development approach that promotes a tighter vertical integration of command-and-control systems (e.g., C4ISR) with the autonomous vehicle control systems that they task.

3.3 Define Standards and Protocols for Unmanned Aerial Vehicle Control. The ASN(RD&A) should continue to support ongoing Department of Defense efforts to define standards and protocols for unmanned aerial vehicle control, in coordination with the efforts of the Defense Advanced Research Projects Agency and the Air Force.

3.4 Expand Involvement in the Space Based Radar Program. The Department of the Navy should expand its initial interaction and involvement in the Space Based Radar program to determine if that program is in the best interest of the Navy in terms of satisfying the Navy's ocean surveillance requirements. Communications connectivity and analysis systems necessary to exploit space-based radar (SBR) surveillance data and to plan and control SBR maritime surveillance missions should be given particular consideration. The CNO should direct liaison with both the Joint Staff (in particular, J6—Joint Staff experts on command, control, communications, and computers) and the unified combatant commanders in order to develop plans and procedures for obtaining access to SBR resources if required.

INCORPORATE LEVEL OF AUTONOMY AS SYSTEM DESIGN TRADE-OFF

System designers of autonomous vehicles often neglect the potential operational benefits to be derived by employing level of mission autonomy as a design choice in up-front trade-off studies, instead electing to focus on trade-offs relating to vehicle performance characteristics (e.g., speed, range, endurance, stealth) and subsystem capability (e.g., sensing and communications). This approach constrains the level of autonomy that can be implemented later in the development and prevents designs that might provide greater operational benefit in terms of impacting mission effectiveness, vehicle survivability, and system affordability.

Recommendation 4: The Assistant Secretary of the Navy for Research, Development, and Acquisition (ASN(RD&A)) should mandate that level of mission autonomy be included as a required up-front design trade-off in all unmanned vehicle system development contracts. Specifically:

4.1 Incorporate Level of Mission Autonomy as an Autonomous Vehicle Design Trade-off. The ASN(RD&A) should direct appropriate agencies in the Navy and Marine Corps to exploit level of mission autonomy as a degree of freedom for impacting concepts of operations, mission effectiveness, vehicle survivability, and system affordability by including a level of mission autonomy as a design choice in the early-stage system trade-off studies. The architecture of all new autonomous vehicles should be such that increasing levels of autonomy can be implemented in the field by modular replacement and/or software upgrade.

1

Introduction

BACKGROUND

Committee Definition of "Autonomous Vehicles"

One of the first topics addressed by the Committee on Autonomous Vehicles in Support of Naval Operations as it began this study was its definition of the term "autonomous vehicles." To avoid a prolonged debate over how much "intelligence" is required for a vehicle to be considered "autonomous," the committee elected to include within the scope of this report all relevant vehicles that do not have a human onboard. Moreover, an autonomous vehicle is an unmanned vehicle with some level of autonomy built in—from teleoperations to fully intelligent systems. Unmanned aerial vehicles (UAVs), unmanned surface vehicles (USVs), unmanned undersea vehicles (UUVs), and unmanned ground vehicles (UGVs) have some level of autonomy built in; the committee uses the acronym "AV" to refer to all such autonomous vehicles. While this definition of an AV as an unmanned vehicle with some level of autonomy built in is broad enough to include weapons systems such as torpedoes, mobile mines, and ballistic and cruise missiles, these systems may be mentioned peripherally but are not discussed in this report. Nor are space vehicles, although space-based applications such as enhanced command, control, and communications (C3) are discussed in terms of their enabling autonomous vehicles.

Past Use of Autonomous Vehicles

Autonomous vehicles (AVs) have been used in military operations for more than 60 years, with torpedoes, cruise missiles (e.g., the German V-1 in World War II), satellites, and target drones being early examples. They have also been widely used in the civilian sector (e.g., by first-responders for the disposal of explosives, by those engaged in work and measurement in radioactive environments, by various offshore industries for both creating and maintaining undersea facilities, by researchers in atmospheric and undersea activities, and by industry in automated and robotic manufacturing).

This report is primarily forward-looking, building on recent AV successes experienced during military operations in Kosovo, Afghanistan, and Iraq. However, it is instructive to look briefly at the history of U.S. military Service use of AVs, some of which is summarized in Table 1.1; the table also contains lessons learned that are believed to have continuing value.

U.S. MILITARY OPERATIONAL ENVIRONMENT, PRESENT AND FUTURE

The primary threats to the security of the United States today are nonstate actors and rogue nations, with the potential rise of a serious military competitor in the future. The likelihood of conflict appears to be on the increase, and anticipating the next theater of war is more difficult now than in the recent past. The proliferation of weapons of mass destruction continues to be a fundamental concern. In addition, the importance of stability operations in which U.S. forces are employed as peacekeepers on foreign soil is increasing. Furthermore, while the American people appear to be very supportive of military initiatives, they are also increasingly concerned with limiting losses to U.S. military personnel and reducing collateral damage. As a result, "dull, dangerous, or dirty" tasks (e.g., mine clearance listed in Table 1.1) could continue to be performed by AVs.

The current U.S. defense strategy has as primary elements homeland defense, strategic deterrence, and the capability to conduct simultaneous conventional military operations as well as special operations in the war on terror. The role of the Department of Defense (DOD) in homeland defense is being defined as the Department of Homeland Security establishes itself. In this context, the U.S. Navy is being called upon to increase its collaboration with the U.S. Coast Guard.

The nation's conventional forces are expected to be able to deter aggression in any four critical regions and to win decisively in one. The often geographically distributed threats and their uncertain nature today stress the size and operational tempo of U.S. forces. It is widely expected that smaller but highly capable and determined adversaries will employ asymmetric means to oppose U.S. forces. In many cases these means could be directed at naval forces—for example, the use of mines or the threat of supersonic, sea-skimming cruise missiles to slow down operations, which can cause failure at the campaign level.

The Trend Toward Joint Operations and Acquisition

An important trend relevant to the subject of autonomous vehicles in support of naval operations is the move toward jointness in U.S. military operations and in acquisition. In recent years almost all U.S. military operations of any conse-

TABLE 1.1 Past U.S. Military Use of Autonomous Vehicles (AVs)

AV Operations	AV Type	Service	Use/Deployment	Lessons
Drones	UAV, USV, UUV, UGV	Navy, Marine Corps, Army, Air Force	Current	• Multiple-vehicle control (UAVs)—maximum of four could be controlled • Most dollars invested in drone UAVs
Operation Crossroads	USV	Navy	Radioactive measurement, 1940s, South Pacific islands	• AV utility demonstrated for measurements in "dirty" environments
DASH (small helicopter)	UAV	Navy	Antisubmarine warfare weapons carrier, 1958 to 1969; gunfire spotting and reconnaissance in Vietnam, 1968 to 1972	• Radar guidance range eventually exceeded by sonar systems' range • Unreliability of low-cost electronics • Need for clear ownership—acquired by NAVAIR but ship-operated • Reliability/deconfliction/training interconnection • AV flexibility for new CONOPS
Controlled unmanned recovery vehicle	UUV	Navy	Practice torpedo retrieval; retrieval of hydrogen bomb, 1966	• Combined successfully ad hoc with manned vehicle systems to find and retrieve hydrogen bomb (Alvin)[a]
Abrams (tank)	UGV	Army	Mine clearance in Bosnia and Kosovo	• Large robotic systems teleoperated successfully
Remote Ordnance Neutralization System	UGV	Navy	Explosive ordnance disposal, since 1996	• Small robotic systems teleoperated successfully

continued

TABLE 1.1 Continued

AV Operations	AV Type	Service	Use/Deployment	Lessons
Matilda (mini-tank)	UGV	Army, Marine Corps	Tunnel and pipe exploration, since 1999	• Small robotic systems teleoperated successfully
Pioneer (reconnaissance vehicle)	UAV	Army/Navy (to 2000)/ Marine Corps	Desert Storm battleship fire spotting; reconnaissance in Afghanistan and Iraq	• Difficulty of ship retrieval • Environmental sensitivity • Problem with fuel type
Lightning Bugs/ Buffalo Hunter (operations reconnaissance drone)	UAV	Air Force	In Vietnam: reconnaissance, ELINT, electronic warfare, battle damage assessment in heavily defended areas	• C-130-launched, helicopter retrieval successful • Progressively increased autonomy with multitasking/multimission high- and low-altitude maneuvering • "Sacrificial" missions successfully conducted • High support costs
Aquila (remotely piloted vehicle)	UAV	Army	Development cancelled in 1989	• Increased cost and size resulting from "mission creep" and congressional "joint" edict
Near-term Mine Reconnaissance System	UUV	Navy	Deployed on selected submarines, from 1998 to 2003	• Follow-on Long-range Mine Reconnaissance System to be untethered

[a]Alvin is a U.S. Navy-owned deep submergence vehicle (DSV) operated by the Woods Hole Oceanographic Institution as a national oceanographic facility.
NOTE: A list of acronyms is provided in Appendix D.

quence have been conducted with forces drawn from more than one Service. Increasingly these forces have been integrated. Similarly, major military systems are more frequently being acquired jointly, either through a joint agency (e.g., the Missile Defense Agency) or through a Service selected as executive agent for the procurement of systems for more than one Service.

Department of Defense Vision for Transformation

Beginning with its issuance of *Joint Vision 2010*[1] in 1993, the Department of Defense has presented a vision for a future force—distributed and networked; rapidly deployable; with the capability to "observe, plan, and execute" on time lines within the adversary's decision cycle; and capable of highly effective operations, denoted as precision engagement, providing full-dimensional protection, dominant maneuver, and focused logistics. In 2000, *Joint Vision 2020*[2] extended and refined the vision. The 2001 *Quadrennial Defense Review Report* (QDR)[3] identified six operational goals of a transformed force: (1) protect critical bases of operation (including the U.S. homeland); (2) protect and sustain U.S. forces in distant antiaccess or area-denial environments and defeat antiaccess threats; (3) deny sanctuary to enemies through persistent surveillance, tracking, and rapid engagement with high-volume precision strikes; (4) assure information systems in the face of attack and conduct effective and discriminating offensive information operations; (5) enhance the capability and survivability of space systems and supporting infrastructure; and (6) leverage information technology and innovative concepts to develop an interoperable, joint command, control, communications, computers, intelligence, surveillance, and reconnaissance (C4ISR) architecture and capability that includes an adaptable joint operational picture.

The 2001 QDR also defined four pillars of a strategy for force transformation: (1) strengthen joint operations, (2) exploit U.S. intelligence advantages, (3) experiment in support of new warfighting concepts, and (4) develop transformational capabilities. As guidance on the fourth pillar of this strategy, *Transformation Planning Guidance,*[4] released in 2003, offered the following principle: A

[1]GEN John M. Shalikashvili, USA, Chairman of the Joint Chiefs of Staff. 1996. *Joint Vision 2010*, U.S. Government Printing Office, Washington, D.C. Available online at <http://www.dtic.mil/jv2010/jvpub.htm>. Accessed on May 13, 2005.

[2]GEN Henry H. Shelton, USA, Chairman of the Joint Chiefs of Staff. 2000. *Joint Vision 2020*, U.S. Government Printing Office, Washington, D.C., June. Available online at <http://www.dtic.mil/jointvision/jv2020.doc>. Last accessed on April 5, 2004.

[3]Donald H. Rumsfeld, Secretary of Defense. 2001. *Quadrennial Defense Review Report,* U.S. Government Printing Office, Washington, D.C., September 30. Available online at <http://www.defenselink.mil/pubs/qdr2001.pdf>. Accessed on May 13, 2005.

[4]Donald H. Rumsfeld, Secretary of Defense. 2003. *Transformation Planning Guidance,* U.S. Government Printing Office, Washington, D.C., April. Available online at <http://www.defenselink.mil/brac/docs/transformationplanningapr03.pdf>. Accessed on May 13, 2005.

transformational capability is one that enables (1) superior information position, (2) high-quality shared awareness, (3) dynamic self-coordination, (4) dispersed forces, (5) de-massed forces, (6) deep sensor reach, (7) compressed operations and levels of war, (8) rapid speed of command, and (9) ability to alter initial conditions at increased rates of change. As addressed in the following chapters, achieving these capabilities poses new challenges to AVs in terms of their availability (relating to endurance, environmental sensitivity, vulnerability, logistics, and reliability), their cooperability, interoperability, and deconfliction with other systems, their flexibility and modularity, and their cost. Advances in AVs are enabled (and limited) by progress in the technologies of computing and robotics, navigation, communications and networking, power sources and propulsion, and materials.

THE PROMISE OF AUTONOMOUS VEHICLES

It is the thesis of this report that autonomous vehicles have the potential to contribute significantly to achieving many of the capabilities cited above from *Transformation Planning Guidance*, and that AVs thus qualify as providing potentially transformational capabilities.

As the autonomy level of AVs increases, the number and complexity of the missions that they can perform will increase—with the added benefit of their being able to perform missions not previously feasible simply owing to the risk involved or to a lack of available human operators. The potential advantages of fully autonomous vehicles are that they can enable a force that is mission-capable with fewer personnel, capable of more rapid deployment, and easier to integrate into the digital battlefield.

One can define different levels of autonomy that are appropriate for different missions (as discussed in Chapter 3). The level that includes waypoint navigation (en route navigation changes) and manual command of the payload may be adequate for present-day missions, but it does not provide a truly transformational capability.

More complex tasks require more decision-making capability. The Global Hawk intelligence, surveillance, and reconnaissance (ISR) UAV, for example, can choose between imaging and maneuvering when maneuvering would ruin an image. It can also choose an alternate airport when necessary, without operator input if communications are lost. However, these are still programmed choices, and the decision hierarchy must be anticipated at the mission-planning stage, which is more similar to traditional expert-system programming than to the still-developmental neural network, genetic algorithm, or more modern artificial intelligence techniques. Unless it has sustained high-bandwidth communications to a human operator, an unmanned aerial vehicle engaged in combat or in mixed aircraft operations needs a high level of autonomy in order to sense situations and make complex evaluations and action decisions. Likewise, for unmanned ground, surface, or underwater vehicles, increased autonomy allows more complex missions and provides more value to the user, especially for those systems to which sustained communications are not feasible.

ORGANIZATION OF THE REPORT

Following the Executive Summary and this brief introduction to the report, which provides the committee's definition of the term "autonomous vehicles," Chapter 2 contains a discussion of the naval operational environment and vision for the Navy and Marine Corps and of naval mission needs and potential applications and limitations of AVs. Chapter 3 discusses autonomy technology—including the state of the art of today's autonomous systems and levels of autonomy. Chapter 4 focuses on the capabilities and potential of unmanned aerial vehicles. Chapter 5 focuses on unmanned surface and undersea vehicles, and Chapter 6 discusses unmanned ground vehicles. Each of these chapters discusses the potential of AVs for naval operations, the operational needs and technology issues, and the opportunities for improved operations. Chapter 7 discusses the integration of autonomy in network-centric operations, including UAV command and control, UAV communications, ISR and UAVs, interoperability issues for AVs, and space-based systems. Chapters 3 through 7 present the committee's conclusions and recommendations.

Appendix A provides brief biographies of the members of the committee. Appendix B offers a technical discussion of AV scaling, energy, sensing, communications, and related topics. Appendix C provides more details on the UAV system descriptions. Appendix D is a list of acronyms and abbreviations.

2

Naval Vision: Operations and Autonomous Vehicle Applications

This chapter describes the naval vision of operations and the potential for autonomous vehicle (AV) applications within the context of that future vision. The section below summarizes the naval operational environment and vision for the U.S. Navy and Marine Corps. Subsequent sections then address specific naval mission needs and potential applications and limitations of autonomous vehicles.

NAVAL OPERATIONAL ENVIRONMENT AND VISION

Broadly speaking, the role of the Navy and Marine Corps in the U.S. military is to provide credible, sustained combat power from the sea when and where it is needed.[1] Many future naval combat operations are likely to be in the littorals, that is, close to shore, in order to project power ashore and to provide an umbrella of defense for forces ashore. In the littorals, naval operations are expected to be contested with mines, diesel submarines, swarms of small boats, and antiship cruise missiles. Marine expeditionary operations can be contested by shore batteries, ground forces, and mines in the surf, on the beach, and inland. In addition, there may be Marine Corps objectives in urban terrain, a complex environment that compounds the difficulties of combat operations and increases risk. If a serious military competitor arises in the future, there is the possibility of war at sea (i.e., opposing naval forces engaging on the high seas).

[1]ADM Vern Clark, USN, Chief of Naval Operations; and Gen Michael W. Hagee, USMC, Commandant of the Marine Corps. 2003. *Naval Operating Concept for Joint Operation,* U.S. Government Printing Office, Washington, D.C., September 22.

Navy Vision and Environment

The vision of the Navy's capstone concept Sea Power 21[2] is summarized in the concepts of Sea Strike, Sea Shield, and Sea Basing, enabled by FORCEnet, as described briefly below.

Sea Strike

Sea Strike is a broad concept for projecting precise and persistent offensive power from the sea. According to this concept, networked, autonomous, organic, long-dwell naval sensors, integrated with national and joint systems, will provide persistent intelligence, surveillance, and reconnaissance (ISR), enabling the development of a comprehensive understanding of an adversary's capabilities and vulnerabilities. Closely integrated with these ISR assets will be the capability to strike time-sensitive and moving targets so as to defeat any plausible enemy force.

Sea Shield

Sea Shield is the concept focused on the protection of national interests by sea-based defense resources. Traditionally, the Navy has maintained vital sea lines of communication, protected its own offensive forces, and provided strategic deterrence through nuclear-armed submarine patrols. Under Sea Shield, in the future the Navy will also project an umbrella of theater air defense ashore, assist in providing ballistic missile defense for the U.S. homeland and for forces in theater, and extend the security of the United States seaward by detecting and intercepting vessels of hostile intent.

Sea Basing

As stated in "Sea Power 21," "As enemy access to weapons of mass destruction grows, and the availability of overseas bases and ports declines, it is compelling both militarily and politically to reduce the vulnerability of U.S. forces through expanded use of secure, mobile, networked sea bases."[3] Sea Basing will support versatile and flexible power projection, enabling forces up to the size of a Marine Expeditionary Brigade (MEB) to move to objectives deep inland. More than a family of platforms afloat, Sea Basing will network platforms among the

[2]ADM Vern Clark, USN. 2002. "Sea Power 21: Projecting Decisive Joint Capabilities," *U.S. Naval Institute Proceedings*, Vol. 128, No. 10, pp. 32-41.

[3]ADM Vern Clark, USN. 2002. "Sea Power 21: Projecting Decisive Joint Capabilities," *U.S. Naval Institute Proceedings*, Vol. 128, No. 10, pp. 32-41.

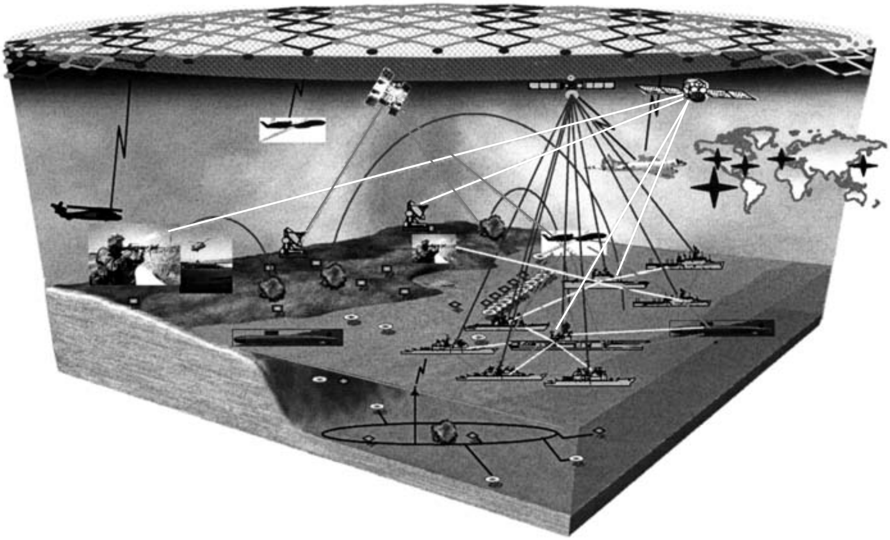

FIGURE 2.1 Schematic portrayal of the Navy's vision of FORCEnet. SOURCE: CAPT Robert Tylicki, USN, Deputy Branch Head for FORCEnet Requirements, OPNAV N61FB, "FORCEnet—Making Network Centric Warfare a Reality," presentation to the committee, January 30, 2003.

Expeditionary Strike Group (ESG), the Carrier Strike Group (CSG), the Maritime Prepositioning Force (MPF), the Combat Logistics Force (CLF), and emerging high-speed sealift and literage technologies. It will enable Marine forces to commence sustainable operations and enable the flow of follow-on forces into theater and through the sea base, as well as expediting the reconstitution and redeployment of Marine forces for other missions.

FORCEnet

FORCEnet is the Chief of Naval Operations' (CNO's) vision for enabling network-centric operations for the Navy (see Figure 2.1). According to the CNO, FORCEnet is the "operational construct and architectural framework for naval warfare in the information age, integrating warriors, sensors, command and control, platforms, and weapons into a networked, distributed combat force."[4] While broader in concept than just communications networks, it includes "dynamic, multi-path and survivable networks" among the capabilities to be provided.

[4]ADM Vern Clark, USN. 2002. "Sea Power 21: Projecting Decisive Joint Capabilities," *U.S. Naval Institute Proceedings*, Vol. 128, No. 10, p. 37.

Marine Corps Vision and Environment

The Marine Corps vision is encapsulated in the concepts of Expeditionary Maneuver Warfare (EMW), which serves as the Marine Corps's capstone concept for the 21st century.[5] EMW includes the following:

- Operational Maneuver From the Sea (OMFTS),[6] the concept for the projection of maritime power ashore, focusing on the operational objective using the sea as a maneuver space and pitting strength against weakness with overwhelming tempo and momentum; and
- Ship-to-Objective Maneuver (STOM),[7] the concept that applies the principles and tactics of maneuver warfare to the littoral battlespace.[8]

Consistent with the philosophy espoused in *Joint Vision 2010*[9] and *Joint Vision 2020*,[10] Marine Expeditionary Forces (MEFs) are envisioned as being rapidly deployable, distributed and networked, taking advantage of information superiority and speed of execution to cut off an adversary's options. Central to the vision is the ability to deploy STOM directly from ships in the sea base to inland objectives, without the necessity of seizing, defending, and fortifying staging areas on the beach. Expeditionary Maneuver Warfare depends significantly on enhanced joint ISR capability, improved command and control (C2), and new platforms that will enable assault forces to maneuver rapidly to strike an enemy at its weakest points in the battlespace. The concept is likely to require moving a combat-credible ground force several hundred miles inland with great speed and sustaining it there for considerable periods of time.

On the ground and in urban terrain, distributed Marine forces will maneuver in a coordinated advance to exploit enemy weaknesses. This will require command and control, assured communications, persistent ISR with supporting firepower, and effective air defense.

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[5]Gen James L. Jones, USMC, Commandant of the Marine Corps. 2001. *Expeditionary Maneuver Warfare: Marine Corps Capstone Concept,* Warfighting Development Integration Division, Marine Corps Combat Development Command, Quantico, Va., November 10.

[6]Headquarters, U.S. Marine Corps. 1996. *Operational Maneuver From the Sea,* U.S. Government Printing Office, Washington, D.C., January 4.

[7]LtGen Paul K. Van Riper, Commanding General, Marine Corps Combat Development Command. 1997. *Ship to Objective Maneuver*, Quantico, Va., July 25.

[8]ADM Vern Clark, USN, Chief of Naval Operations; and Gen Michael W. Hagee, USMC, Commandant of the Marine Corps. 2003. *Naval Operating Concept for Joint Operation,* U.S. Government Printing Office, Washington, D.C., September 22.

[9]GEN John M. Shalikashvili, USA, Chairman of the Joint Chiefs of Staff. 1996. *Joint Vision 2010*, U.S. Government Printing Office, Washington, D.C. Available online at <http://www.dtic.mil/jv2010/jvpub.htm>. Accessed on May 13, 2005.

[10]GEN Henry H. Shelton, USA, Chairman of the Joint Chiefs of Staff. 2000. *Joint Vision 2020*, U.S. Government Printing Office, Washington, D.C., June. Available online at <http://www.dtic.mil/jointvision/jv2020.doc>. Last accessed on April 5, 2004.

NAVAL MISSION NEEDS AND POTENTIAL APPLICATIONS OF AUTONOMOUS VEHICLES

Among the world's naval forces, the U.S. Navy and Marine Corps are second to none, and at present they have no close competitor. However, the current national security environment places increased demands on the Navy and Marine Corps—for presence in a larger number of strategically important geographic locations than in the past, for more rapid and flexible response to emerging crises, and for new capabilities to enable decisive victory over determined adversaries employing asymmetric means.

As the post-Cold War era has evolved, it has become increasingly clear that many military legacy systems have minimal or no utility in meeting many emerging challenges. As part of the ongoing transformation of the U.S. military Services, the envisioned Navy and Marine Corps concepts of operation require a transformation of naval forces. And, as discussed below, autonomous vehicles will play a major role in the transformed force. These discussions note that although an AV may have the capability to perform a task, it is not necessarily better than manned systems in performing the task. All else being equal, AVs with a high degree of autonomy can potentially reduce training, support rapid change in tactics (i.e., capitalize more rapidly on the digital battlefield), enable reductions in force personnel, and help reduce the logistics footprint, to name a few advantages.

The rest of this section discusses the potential AV applications to meet the needs of Sea Strike, Sea Shield, ground warfare, and other missions.

Sea Strike: Needs and Potential Autonomous Vehicle Applications

Today the Navy and Marine Corps project power ashore against ground targets by three primary means: (1) manned strike aircraft that are carrier-based or based on large-deck amphibious assault ships (LHDs/LHAs) and that carry precision weapons, (2) cruise missiles launched from surface ships and submarines, and (3) Marine Expeditionary Forces transported ashore from amphibious support ships by manned amphibious landing craft, amphibious assault vehicles, and helicopters. The sea-launched cruise missiles and frequently the air-launched precision weapons are targeted using coordinates obtained by means of electro-optical (EO) or infrared (IR) imagery, often from national intelligence resources. With adequate cueing and good weather, strike aircraft have capable sensors enabling them to detect and identify targets. According to recent studies,[11] naval strike capabilities against known, fixed targets are good. However, considerable

[11]For example, Task Force on Options for Acquisition of the Advanced Targeting Pod and Advanced Targeting FLIR Pod. 2001. *Report of the Defense Science Board Task Force on Options for Acquisition of the Advanced Targeting Pod and Advanced Targeting FLIR Pod (ATP/ATFLIR),* Office of the Under Secretary for Acquisition, Technology, and Logistics, Washington, D.C., February.

improvement is needed in strike capabilities against time-sensitive or moving targets, in large part because of surveillance and targeting limitations, especially in adverse weather. Furthermore, there is only minimal capability for detecting, intercepting, or even reacting to opposing forces employing asymmetric means.

Sea Power 21 envisions future naval forces employing autonomous vehicles in a number of Sea Strike mission roles, ranging from surveillance and targeting to weapons delivery. The Navy has been slow to adopt AVs for Sea Strike, and one significant impediment in this regard is that operational forces have been given little opportunity to experiment with AVs and to experience their usefulness. In order to provide operational experience useful for evolving operational concepts and for defining requirements, many currently operational AVs and prototype AVs could be employed by the Navy. Operational experience thus gained can serve to accelerate the introduction of AVs and realize the Sea Strike capabilities envisioned in Sea Power 21.

Modeling and simulation, virtual and constructive, could play an important role in this area, particularly for experimenting with less mature systems and concepts. Such experimentation in simulation could accelerate the development of requirements, and could focus and help integrate research and development (R&D) efforts.

Surveillance and Targeting

Persistent (or continuous) surveillance and targeting of threats constitute an important goal expressed in the DOD's 2001 Quadrennial Defense Review[12] and in the Navy's Sea Power 21, and the goal is critical to the STOM concept of the Marine Corps as well. The most likely path to the successful achievement of this goal for all Services is to have sensor platforms of various kinds deployed and to integrate them into a network.

An effective, persistent surveillance and targeting network is likely to consist of national imaging and electronic intelligence (ELINT) sensors, a constellation of space-based radars, manned aircraft such as the Joint Surveillance Target Attack Radar System (JSTARS) and the U-2, and various kinds of unmanned aerial vehicles (UAVs) and unattended ground sensors (UGSs), depending on the specific mission. In most circumstances, high-altitude and -endurance (HAE) UAVs (such as the Global Hawk) and medium-altitude and -endurance (MAE) UAVs (such as the Predator) can be key contributors to the network. Regardless of whether or not the Navy owns or controls these UAV assets, the data acquired by them are likely to be crucial in developing an accurate and timely picture of the battlespace.

[12]Donald H. Rumsfeld, Secretary of Defense. 2001. *Quadrennial Defense Review Report,* U.S. Government Printing Office, Washington, D.C., September 30. Available online at <http://www.defenselink.mil/pubs/qdr2001.pdf>. Accessed on May 13, 2005.

As another key part of a persistent surveillance and targeting network, Navy strike groups need to have organic sensor platforms. The reasons for this are as follows:

- For the foreseeable future, the majority of the U.S. military theater surveillance and targeting capabilities will be supplied by the U.S. Air Force. Whether or not a network exists, ships on the scene have an obligation to the Joint Force Commander to contribute to surveillance and targeting.
- The proximity of the Expeditionary Strike Groups or Carrier Strike Groups to the target gives them an advantage over other potential sources of surveillance and targeting information (e.g., an ability to perform a given task rapidly).
- Surveillance and targeting coverage from national and theater sources may be missing under some circumstances, possibly at a time when the need for targeting data is urgent and acute. Such a situation could occur when cloud cover blinds the EO and IR sensors on satellites and high-altitude aircraft. In such circumstances, ship-based organic assets could fly below most cloud cover to obtain the needed information.
- The organic sensor platform can have special capabilities that other elements of the network lack (e.g., the ability to approach the target closely and view it from many aspects in a timely fashion).

To provide surveillance and targeting for Sea Strike, the organic surveillance and targeting platform needs to be capable of being launched from ships in the naval force so that it can be on station in a timely fashion and capable of providing data to enable the detection and identification of ground targets of interest. This platform will require the following capabilities:

- Range from the force of no less than weapon delivery range,
- Position accuracy commensurate with that of weapons (certainly no less than that of the Global Positioning System (GPS)),
- Endurance and survivability for the length of attack (certainly more than several hours), and
- Minimal risk to U.S. personnel.

The detection and identification of targets could be accomplished either by humans using data linked back to a ship or ground station or by the platform itself. Speed, endurance, and survivability requirements for the platform would depend on the specific task to be carried out. UAVs appear to be primary candidates for the organic platform role. A recent Defense Science Board study[13]

[13]Task Force on Options for Acquisition of the Advanced Targeting Pod and Advanced Targeting FLIR Pod. 2001. *Report of the Defense Science Board Task Force on Options for Acquisition of the Advanced Targeting Pod and Advanced Targeting FLIR Pod (ATP/ATFLIR),* Office of the Under Secretary for Acquisition, Technology, and Logistics, Washington, D.C., February.

examined various trade-offs in allocating the burden of performance between the targeting system and the weapon to achieve a precision kill. This trade-off will not be considered further here, but it is an area that could benefit from further investigation, especially for UAVs.

The following subsections describe the naval forces' specific Sea Strike surveillance and targeting needs in executing the tasks of naval fire support and deep strike.

Surveillance and Targeting for Fire Support. The Navy is currently designing the DD(X) ship, a destroyer, to have a significant capability for naval fire support. The ship's Advanced Gun System (AGS) will have a higher rate of fire, much greater range, and possibly a larger magazine than that of 5-in. guns on today's surface combatants. With high accuracy, the AGS will fire a rocket-propelled guided munition to hit targets designated by GPS coordinates.

Unless programmatic directions change, it appears that Navy surface ships will have little organic capability to provide target coordinates for the AGS when it becomes operational. As discussed above, for the surveillance and targeting of ground targets, the DOD and the Navy can deploy sensor platforms of various kinds, including HAE and MAE UAVs, and integrate them into a surveillance and targeting network. As also discussed above, in order to provide surveillance and targeting for Sea Strike, a surface ship needs to be capable of launching its own surveillance and targeting platform. For a surface ship with AGS, the platform's range needs to be at least equal to AGS range and to be able to provide targeting data at a rate enabling all AGS batteries in the force to fire at maximum rate. A vertical-takeoff-and-landing (VTOL) UAV appears to be a strong candidate for this role.

Surveillance and Targeting for Ship-to-Objective Maneuver. As part of the Marine Corps STOM concept, in addition to forces crossing a beach in amphibious vehicles, some elements of a Marine Air Ground Task Force (MAGTF) will be transported several hundred miles by VTOL aircraft (such as the MV-22 tilt rotor) and may have to be supported there for extended periods of time. As indicated earlier, the Marine Corps will rely heavily on Navy and Maritime Prepositioning Force (Future) (MPF(F)) ships offshore for fire support, air defense cover, and logistics support for such maneuvers. The Navy currently has no ship-based capability to provide the level of ISR required. Both shore- and ship-based AVs are a likely prospect to meet this need.

Surveillance and Targeting for Deep Strike. As discussed above, persistent surveillance and targeting for deep strike are best met with a network of sensors of different kinds, including both joint and organic UAVs. The organic UAV needs to be capable of carrier launch and recovery and to have range equal to that of the task force's deep-strike weapons, together with significant endurance.

Weapons Delivery and Suppression of Enemy Air Defenses

An uninhabited combat air vehicle (UCAV) is potentially a very attractive means of weapons delivery. It blends the best characteristics of today's cruise missiles and tactical aircraft precision weapons systems. In just a dozen years since their first use in Operation Desert Storm, cruise missiles have become vital components in the U.S. arsenal. They have been widely used in a number of limited engagements since that time and have been used routinely in significant numbers early in major conflicts (e.g., Operation Iraqi Freedom) before enemy defenses have been eliminated. Cruise missiles are accurate, reliable, and survivable, and they do not put pilots at risk, but since theirs is a one-way mission, they are also a relatively expensive way to put bombs on target. Alternatively, carrier-based tactical aircraft can close to within a few miles of a target area and drop inexpensive GPS-guided munitions or laser-guided bombs onto multiple targets and return to the carrier to reload, but of course these operations put pilots at risk. UCAVs combine the best features of these capabilities.

Another potential mission for a UCAV is suppression of enemy air defense (SEAD) (see Figure 2.2). Today this mission is accomplished with manned air-

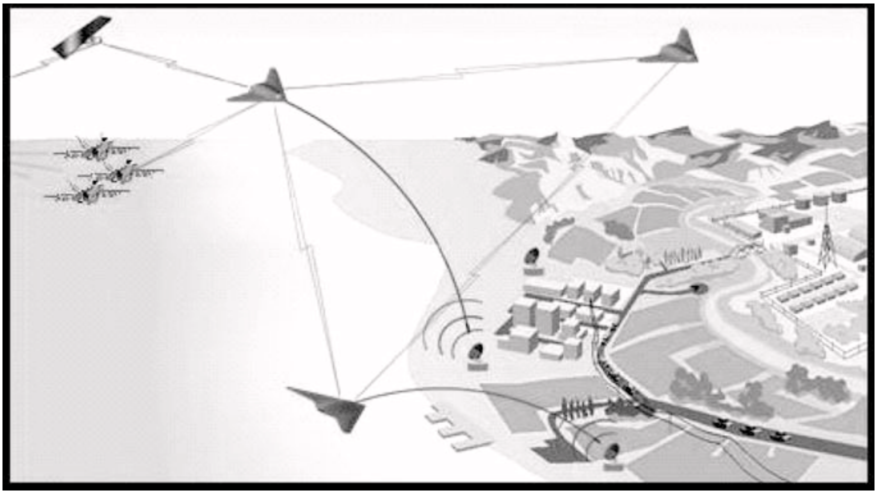

FIGURE 2.2 As illustrated in this schematic, a Joint Unmanned Combat Air System suppression of enemy air defense (SEAD) mission requires coordinated control of multiple unmanned aerial vehicles. SOURCE: Glenn D. Colby, Navy Chief Engineer for Joint Precision Approach and Landing System (JPALS) and Lead for Naval Unmanned Combat Air Vehicles Carrier Air Operations Development, Naval Air Systems Command, "UCAV-N, Naval Unmanned Combat Air Vehicles, Carrier Integration Challenges, Automatic/Autonomous Flight Operations," presentation to the committee, April 24, 2003.

craft, but it is dangerous for them, as explained below. Since the Air Force retired the EF-111 from service many years ago, the EA-6B aircraft has been the DOD's only platform capable of providing electronic jamming support to tactical strike aircraft. As stealth alone is inadequate protection against networked air defenses, jamming support is seen today as a necessary adjunct to all manned deep-strike missions. Though its electronic warfare capabilities are modern, the EA-6B airframe itself is aging, and the Navy is developing a SEAD variant of its F/A-18 E/F aircraft to replace the EA-6B. But the SEAD mission is a dangerous one for a manned aircraft: the high-power jamming transmitters are an unavoidable liability—multiple ground sites can triangulate and locate the aircraft, and antiradiation missiles can home on the transmitters as on a beacon. A UCAV, perhaps using a data link to a ground station for control of the jamming suite, appears to be a strong candidate for this role in the future.

A special potential application of a UAV in the SEAD mission is as a "stand-in," as opposed to a "stand-off," jammer. Modern microwave radars are capable of adaptive nulling that can render ineffective the jammers standing off at a distance. To the degree that our adversaries employ this technique in the future, it may be necessary to jam from a vantage closer to the protected forces, and a UAV appears to be the best platform for this mission.

Sea Shield: Needs and Potential Autonomous Vehicle Applications

The most serious potential threats that the surface Navy and Marine forces may encounter when entering a littoral region are mines in the sea and surf, on the beach, and on land; diesel submarines; swarms of small craft; and antiship missiles (ASMs).

Countering Mines, Submarines, and Surface Craft Threats

The Navy has begun concept development for a Littoral Combat Ship (LCS), whose purpose is to secure littoral regions for Navy and Marine activities. Navy plans appear to place considerable responsibility on the LCS to protect naval forces from a number of significant asymmetric threats, such as mines, diesel submarines, and swarms of small surface craft. It is planned that the LCS will carry mission-specific modules that can be changed as necessary for various missions, and that those modules will make extensive use of various kinds of AVs.

The LCS appears to be the natural home for certain types or classes of UAVs, unmanned surface vehicles (USVs), unmanned undersea vehicles (UUVs), and unmanned ground vehicles (UGVs). To date, the Navy has concentrated on defining the LCS hull, while much remains to be done to define the concepts of operations and systems for executing missions. In particular, it is yet to be determined how the AVs' sensor systems will detect stealthy submarines and mines;

how AVs of different kinds, carrying different sensors and weapons, might be networked and controlled to conduct missions; and how the interchangeable mission modules might be designed to house, operate, support, and maintain these AV systems.

Countering Mines. Mines are a major impediment to naval forces in the littorals. They are relatively inexpensive and can be widely deployed in the sea, in the surf, on the beach, and on land—and they can be very difficult to detect in any of these environments. The methods employed today for countering mines are cumbersome, very slow, expensive, and inconsistent with the rapid operations envisioned in *Joint Vision 2010*,[14] *Joint Vision 2020*,[15] and *Transformation Planning Guidance*.[16] After decades of alternating periods of very brief emphasis and very long neglect in this area, the Navy now has under way a number of promising developments that together may form the basis for a more effective countermine capability. Since there appears to be no single approach possible for countering mines, a systems approach, such as described below, is the most likely path to success.

Under such an approach, before naval forces enter a littoral area, the combatant commander could use a variety of joint ISR assets to support a joint task force (JTF). National imaging and electronic intelligence systems, manned aircraft with a ground moving target indicator (GMTI) capability, HAE UAVs, or the future space-based radar could provide initial indications and warning of preparations for mining activities in coastal areas of interest to naval forces.

Surveillance data received from the aforementioned systems would cue clandestine reconnaissance assets in the fleet, but such cues would have to be provided in a timely fashion. Navy attack submarines (i.e., the nuclear-powered submarine (SSN) and nuclear-powered guided-missile submarine (SSGN)) would employ UUVs in the littoral areas of interest to begin bottom mapping as well as identification of the boundaries of mined areas. Of equal importance will be the identification of mine-free areas all the way to the beach. This entire process would be accomplished in advance of the arrival of the JTF. The entire area will be kept under surveillance to prevent additional minelaying. In addition, small UUVs can conduct detailed reconnaissance of surf zones, waterways, and port

[14]GEN John M. Shalikashvili, USA, Chairman of the Joint Chiefs of Staff. 1996. *Joint Vision 2010*, U.S. Government Printing Office, Washington, D.C. Available online at <http://www.dtic.mil/jv2010/jvpub.htm>. Accessed on May 13, 2005.

[15]GEN Henry H. Shelton, USA, Chairman of the Joint Chiefs of Staff. 2000. *Joint Vision 2020*, U.S. Government Printing Office, Washington, D.C., June. Available online at <http://www.dtic.mil/jointvision/jv2020.doc>. Last accessed on April 5, 2004.

[16]Donald H. Rumsfeld, Secretary of Defense. 2003. *Transformation Planning Guidance,* U.S. Government Printing Office, Washington, D.C., April. Available online at <http://www.defenselink.mil/brac/docs/transformationplanningapr03.pdf>. Accessed on May 13, 2005.

areas prior to any offensive operation. This reconnaissance is a critical capability for the Navy, but again it must be done in a timely manner.

During the next stage of activity, upon arrival in the mission-objective area, ships assigned to the JTF could begin to employ organic AVs on the basis of information received from the surveillance and reconnaissance assets. A synthetic aperture sonar (SAS) carried on an underwater vehicle or towed by a surface craft can map the sea bottom with enough resolution to allow mine detection. An airborne, blue-green laser radar can penetrate the water to modest depths and detect moored mines. Airborne hyperspectral sensors show promise in detecting and locating some surf mines and land mines. Multiple-method systems need to be employed to provide timely identification of both clear and dangerous areas.

While the various subsurface, surface, and airborne vehicles referred to above could be manned, mine clearing in contested waters is a dangerous operation for which AVs appear to be well suited. Similarly, mine clearing on beaches and on land is a hazardous task for which AVs show significant potential.

Countering Submarines. Diesel submarines of modern design are available on the open market today to anyone who can afford them. Moving slowly through littoral waters, these vessels are difficult to detect, even for the Navy's attack submarines; thus, they constitute a serious threat to a naval force in the littorals.

The diesel submarine threat requires a shallow-water, antisubmarine warfare capability. AVs can play a major role in providing this capability. UUVs can help in detecting and countering submarines by deploying and monitoring various sonar sensors and other seafloor devices, tagging the submarines, and, when appropriate, attacking them. UAVs can also play a role as a platform for sensors such as blue-green laser radars, dipping sonars, and magnetic anomaly detection devices, and for dropping weapons.

Countering Surface Craft. A serious threat to surface ships in a littoral region today is swarms of small boats armed with mounted or shoulder-fired weapons or carrying explosives detonated by ramming one of the ships. The severity of the threat is exacerbated by the potential for very large numbers of boats in such an attack. Potential countermeasures include the following:

- Early detection by theater or organic ISR assets, including manned and unmanned aircraft;
- UAVs or USVs equipped with targeting sensors, a communications link to a human controller, and a weapon such as a rapid-fire gun system; and
- Sensors and gun systems on the surface ships themselves.

Another type of threat could come from an adversary employing commercial ships to attack U.S. ships or port facilities. Also, an open-ocean threat from highly capable enemy forces could arise in the future to challenge the U.S. surface Navy. At present the Navy has inadequate means for surveillance, targeting, and battle damage assessment of enemy surface forces on the high seas. As many studies conducted during the Cold War attest, a system for surveillance and targeting over broad expanses of ocean would be expensive. However, the Air Force is embarked on the development of a space-based radar system for overland surveillance; with modification this system could provide surveillance of the oceans as well. Technologies to provide power to such a system will limit the degree to which both missions can be met simultaneously. An HAE UAV would be a very useful adjunct to a space-based surveillance system, as would carrier-based manned aircraft or UAVs with appropriate sensor systems.[17]

Countering Air Threats

U.S. ships in littoral waters face a serious air threat from antiship missiles launched from aircraft, patrol boats, and ground launch platforms, including mobile ground launchers. Large numbers of ASMs are available worldwide. The targeting and command, control, and communications (C3) requirements for short-range (25 to 50 miles) ASMs, especially ground-launched ASMs, are relatively simple and available to most developing countries. Defense against ASMs starts with the early detection and tracking of the launch platforms. Good understanding of the order of battle (not easy to obtain in many of today's unpredictable scenarios) would permit the identification of which platforms to watch and possibly to preemptively attack, depending on rules of engagement. UAVs capable of detecting ground targets, aircraft, or patrol boats can play a major role in such efforts.

Air defense of surface ships relies on extensive measures, requiring the detection of incoming ASMs at significant distances from the surface force. Because most ASMs are cruise missiles that fly at very low altitude, an elevated platform that detects ASMs over the horizon from the surface force can improve this defense considerably. This task could be accomplished by the E-2 Hawkeye, the Airborne Warning and Control System (AWACS), or JSTARS, if any of these manned aircraft were present. The E-2C (included in the Radar Modernization Program (RMP)) with its new radar should improve ASM detection and tracking. The radar being developed for the Multi-Platform Radar Technology Insertion Program (MP-RTIP) scheduled for the MC2A aircraft is also planned for use in JSTARS and in the HAE UAV Global Hawk. The radars in the MC2A and JSTARS will have a substantial capability for detecting and precision track-

[17]National Research Council. 2005. *The Navy's Needs in Space for Providing Future Capabilities*, The National Academies Press, Washington, D.C.

ing of cruise missiles. The version considered for Global Hawk, although significantly less capable, still can have a useful capability against most cruise missiles.

Without the aircraft mentioned above, naval surface forces will have no elevated platforms for over-the-horizon detection of air threats. While U.S. naval ship defenses have formidable quick-reaction capabilities, an elevated platform *organic* to cruisers and destroyers (frontline air defense ships) would greatly enhance naval air defense. This is a potential role for some type of UAV. USVs with means to amplify their radar signatures can be effective decoys.

Ground Warfare: Needs and Potential Autonomous Vehicle Applications

Ground combat introduces a whole new set of needs, including many that AVs could potentially fill in the future. A few of these needs are being met in rudimentary fashion by AVs today. For example, the Marines have employed the Pioneer UAV for ground surveillance since 1985 and have used it extensively, including most recently during Operation Iraqi Freedom. However, the Pioneer is limited by its short range and endurance and has substantial logistics requirements, and although it can be launched via catapult from a ship, it can be recovered by the ship only with the use of a net in a practice now discontinued.

Looking "Over the Hill"

The often-quoted statement attributed to the Duke of Wellington, "I've spent most of my career wondering what was on the other side of the hill," was largely applicable to U.S. ground forces vis-à-vis enemy ground forces until the appearance of JSTARS with its GMTI radar system in the 1991 Gulf War. Then, for the first time, commanders were able to see the makeup and movement of enemy ground forces at distances of nearly 200 miles. Low-flying UAVs with EO/IR and radar imaging sensors may further enhance the ability to see "over the hill" by covering areas masked from JSTARS and HAE UAVs by buildings or terrain. Additional advantages of such UAVs are their capability to provide the close-up optical views needed to identify some targets and to allow EO/IR surveillance under cloud cover when high-altitude EO/IR views are obscured. These low-altitude UAVs must be small so that they can be launched and controlled by small Marine Corps units. One example of such use was the employment of the Dragon Eye UAV by Marines during Operation Iraqi Freedom.

One of the most serious concerns to the ground warrior is a potential attack with chemical or biological weapons. In the future, UAVs, UGVs, and unattended ground sensors (UGSs) will be able to detect the presence of such agents using sensors that can perform in near real time. Other possible roles for AVs include these: a network of UGSs employing acoustic and visual sensors may be useful for monitoring road traffic, UAVs may be useful for deploying UGSs, and UGVs are expected to be useful in reconnoitering over the hill.

Urban Warfare

Urban warfare is an especially dangerous environment for the ground warrior, and AVs can and should play a critically important role in reducing U.S. casualties in such operations. UAVs, especially vertical-takeoff-and-landing tactical unmanned aerial vehicles (VTUAVs), can provide persistent overhead surveillance using EO/IR, GMTI, signal intelligence (SIGINT), and chemical/biological/radiological sensors. Additionally, the UAV can serve as a communications relay and a pseudolite (ground-based reference station) for GPS extension into built-up areas. For example, a small UAV propelled by a ducted fan and equipped with a television camera and communications link can provide surveillance of an area by perching atop a selected building and/or looking into windows. In the future, armed UAVs would be useful in an urban environment to provide another vantage for fire support to ground forces.

UGVs in a variety of forms can also be particularly useful in urban warfare. Examples are teleoperated machines for looking around corners, semismart small "tanks" containing sensors and weapons, and small devices that a Marine can throw through a window to gather information immediately, implant sensors, or attack the room's occupants. UGVs may be especially useful underground, in sewer systems or subways. A low-cost, teleoperated UGV for simply drawing enemy fire may also be useful. The Marine Corps and Army have a joint program office in the UGV area in which it is most important that the Marine Corps maintain a high priority.

Other Potential Missions

The DOD's missions are changing, and these changes will likely result in new and different missions for the Naval Services and new needs for AVs. For example, HAE UAVs may find application in maritime surveillance for homeland defense and for ballistic missile defense.

A specific mission that cuts across applications discussed above is the collection and dissemination of environmental data. Up-to-date information on the weather in denied areas can be very valuable. Thus, any AV that transmits data to a station can enhance its force's military effectiveness by including weather information in its communication. Instruments to sense environmental conditions are inexpensive and unobtrusive, and communications requirements to transmit the data are minimal.

TABLE 2.1 Potential Applicability of Autonomous Vehicles in Naval Missions

	Autonomous Vehicle Applicability			
Mission and Task	UAV	USV	UUV	UGV
Providing ground surveillance and targeting	•			
For nearshore fire support	•			
For support of Ship-to-Objective Maneuver	•	•	•	•
For deep strike	•			
For suppression of enemy air defenses	•			
For looking over the hill	•			•
For urban warfare	•			•
Countering mines in the sea	•	•	•	
Countering mines in surf on beach	•			•
Countering land mines	•			•
Countering diesel submarines	•	•	•	
Countering surface craft	•	•		
Countering antiship cruise missiles	•	•		
Detecting chemical, biological, radiological attack	•	•		•
Providing maritime surveillance	•			
Environmental monitoring	•	•	•	•

NOTE: UAV, unmanned aerial vehicle; USV, unmanned surface vehicle; UUV, unmanned undersea vehicle; UGV, unmanned ground vehicle.

Little can be said in this unclassified document about AV applications in intelligence operations, but their ability to undertake missions too dangerous or too stressing for humans has made them especially valuable in such roles.

Summary of Potential Applications of Autonomous Vehicles

Table 2.1 lists likely future naval missions and potential applications of AVs.

POTENTIAL AND LIMITATIONS OF AUTONOMOUS VEHICLES

Autonomous vehicles exhibit great potential to enhance naval operations, but they are limited by basic physical principles (see Appendix B). It is useful to examine their future potential while at the same time considering their limitations.

Factors That Limit Autonomous Vehicles

There are several factors that limit AVs from achieving their full capabilities and potential. These factors are discussed in this section.

Cost

AVs show promise for greatly reducing the cost of accomplishing many missions. Because they do not have to provide for the needs of humans for space, life support, and special threat protection (e.g., armor), AVs can often be made much lighter and smaller than they would otherwise have to be. Historically, the cost of a vehicle is roughly proportional to its mass (about $3,300 per kilogram, or $1,500 per pound for a typical military airframe for manned vehicles). Thus, reductions in mass yield substantial savings in procurement costs, often resulting in a proportionate cost savings in the support required for the vehicle.

Cost reduction is such an important consideration that it is worthwhile to project the limits of miniaturization of autonomous vehicles. For example, with sufficient miniaturization and cost reduction, the use of expendable AVs might make some missions feasible that would otherwise be too costly. Such trade-offs need to be carefully considered as the technology for AVs advances.

Although current experience with AVs does not appear to exhibit the level of cost savings now enjoyed by computers, there is good reason to believe that as AV technologies mature and production levels increase, their costs will follow the well-established trends of manned vehicles (i.e., $1,500 per pound).

Onboard Computing

The onboard computing capacity of AVs is likely to continue to follow Moore's law as the commercial technology advances.

Intelligence, Surveillance, Reconnaissance, and Targeting Sensors

In addition to onboard computing, other aspects of AVs, such as imaging sensors, will presumably also continue a rapid advance driven by other markets. However, such systems often have theoretical limits that will restrict further advances in certain areas. For example, many imaging sensors are now able to detect nearly all of the available light entering the camera aperture, with sensor noise near the lower limits set by physical laws. Thus, sensitivity to light will not increase, but improvements to these imaging sensor systems will come mostly in terms of increased total size of the imaging array. Thus, panoramic-type images can be expected; such images preserve the fine detail needed for sophisticated image interpretation.

Advanced sensors for intelligence, surveillance, reconnaissance, and targeting (ISR&T) often require optics that cannot be miniaturized. For example, to recognize faces (~1 cm, or 3/8 in., resolution) in an image taken from 1 km (3,300 ft) away requires a camera aperture of about 10 cm (~4 in.) in diameter. This size is dictated by the wave nature of light and is not subject to miniaturization through the application of advanced technology. Thus, very small AVs, carrying small sensors, will need to approach their targets relatively closely in order to get good ISR&T data, while larger AVs might be able to stand off a considerable distance to accomplish the same purpose. Since the size of the camera aperture is proportional to the range to the target (for the same image resolution), to recognize faces from 10 km would require a 1 m (40 in.) aperture. Thus, if good images of the ground or sea surface are required, a high-altitude reconnaissance UAV would have to be a relatively large vehicle to accommodate a camera of the necessary size.

A similar problem applies to the acoustic sensors used on underwater vehicles, leading also to the conclusion that the longer-range sensors cannot be accommodated in smaller vehicles. However, the wave effects governing acoustic sensors can be somewhat overcome by synthetic aperture sonar by integrating the signal from a moving sensor to get the same resolution as that from a stationary sensor.

In similar fashion, the sensors on UAVs can employ the same techniques as those employed by manned aircraft with synthetic aperture radar (SAR) imaging. However, the application of such phase-coherent techniques to natural visible and infrared (IR) light is so challenging that it will almost certainly not be feasible within the planning horizon of this study, if ever.

Another important physical characteristic of atmospheric sensing is the effect of water vapor on high-frequency electromagnetic radiation. In general, clouds are opaque to electromagnetic radiation at optical and infrared frequencies, while radiation at lower frequencies is not impeded. Hence, radar emissions pass readily through clouds, while optical and infrared images do not. Thus, when clouds or fog obscure the ground, high-altitude UAVs with EO, IR, and radar sensors (e.g., the Global Hawk and the Predator) will lose their EO/IR capabilities, but they will maintain their radar sensing, including SAR and moving target indicator (MTI) capabilities.

Endurance

Characteristically, small vehicles tend to have relatively short ranges and loiter times, whereas larger vehicles can have much greater ranges and loiter times. Physical laws dictate that both aerial and underwater vehicles have approximately the same endurance versus mass relationship. These limitations are exhibited in data for actual vehicles (see Appendix B for a more detailed discussion of the scaling of AVs and a plot of the endurance versus mass relationship). Since a vehicle of a certain size can carry only so much fuel, it can oppose natural winds or ocean currents for a limited amount of time. Most current operational UAVs or UUVs with endurance greater than 24 hours have a gross weight of at least 1 ton. By contrast, small and much lighter-weight aerial or underwater vehicles that can be hand-launched have a maximum endurance of a few hours.

This limitation, which is primarily the result of basic physics, is not readily amenable to improvement by advanced technology. Partly for this reason, the Defense Advanced Research Projects Agency (DARPA) has been funding the development of small rotorcraft that can "perch and stare," and so perform long missions without running out of fuel.

Vehicle Types

There are three broad categories of AVs, which can be characterized by size, that are both feasible and attractive. One type, being very small, has limited sensor resolution and endurance and must get relatively close to the target to perform its mission, as discussed above. Its small size and mass mean that it might be very inexpensive, hand-launched, and "attritable" (expected to survive only a limited number of missions), or even expendable (not retrieved at all). The vehicles in this category can only maneuver for a few hours, but might be able to extend their useful missions by perching, for example, on the local terrain. Such vehicles might be so small and unobtrusive that they would not be very vulnerable, despite the fact that they approach their targets very closely. Current examples of such systems are the Dragon Eye UAV and the Remote Environmental Monitoring Unit System (REMUS) UUV, both of which have demonstrated their operational utility: the Dragon Eye was used by Marines for close-in reconnaissance at the battalion and company levels in the drive to Baghdad during Operation Iraqi Freedom, and REMUS was used to scout the waters of the port of Umm Qasr for mines at the beginning of the same conflict.

Another broad class of AV, somewhat larger, has a dry (unfueled) mass in the range of ~100 kg (220 lb) to a few tons. Depending on its payload, such a vehicle can maneuver as much as a day or two without refueling and carry sensors that can obtain superb reconnaissance data without getting very close to the target. Even though they are moderately large, such vehicles may not be very vulnerable because they can loiter far enough away from a target to be hard to detect. Examples of such systems are the Predator UAV, which has been so successful in the conflicts in Afghanistan and Iraq, and UUVs, which can be deployed from a standard 21-in. diameter torpedo tube to perform missions such as mine hunting using high-resolution, side-scan sonar. These vehicles can be much lighter and much less costly than a piloted vehicle, which can perform the same mission, and they can operate far longer than a lone, onboard, human pilot could endure.

The last broad category of AV is larger still, with a mass of many tons. Such vehicles are suitable for carrying large payloads (e.g., munitions or heavy, power-hungry sensors) or desirable for having extreme range or endurance. While these vehicles may not be very much lighter or cheaper than manned vehicles intended for the same mission, they can operate in extremely hazardous environments and persist for extreme durations (i.e., tens of hours for UAVs). Examples of such vehicles are the Global Hawk UAV; the Navy's planned uninhabited combat air vehicle (UCAV-N); or a large UUV capable of tracking and trailing a submarine (i.e., following a submarine for many days or weeks). A disadvantage of such large vehicles is that, once again, cost is roughly proportional to mass, so they will be relatively expensive.

The foregoing discussion applies mostly to unmanned aerial, undersea, and surface vehicles, with somewhat different physical limitations applying to unmanned ground vehicles. The latter can always simply stop moving in order to reduce or eliminate most power drain. Although "perch and stare" may be developed for rotorcraft UAVs, most aerial vehicles, sea-surface vehicles, and underwater vehicles do not have that option, with the possible exception of a UUV that settles onto the seafloor. However, when UGVs are maneuvering, their energy consumption is not too different from that of the other vehicles. Therefore, it takes a vehicle mass of 1 ton or a few tons to perform sustained maneuvers for more than a day or two, and small vehicles will have maneuvering endurance measured in hours.

One approach to improving the endurance of AVs is through on-station or in-flight refueling. This technology will be very beneficial for certain types of missions. However, because there is generally a severe endurance penalty for moving at high speed, most AVs will be designed to move relatively slowly, so as to have as much endurance as possible. As a result, most UAVs will not be able to fly as fast as the stall speed of the current fleet of refueling tankers maintained by the Air Force. Alternatively, UAVs might autonomously refuel UAVs of similar performance. Refueling of UUVs and USVs probably will require them to dock with or be brought onboard mother ships. For any mission class, there is an important trade-off to consider between on-station refueling and just having another similar vehicle replace the exhausted one.

Communications

In the area of communications, the differences between UAVs, USVs, UUVs, and UGVs begin to emerge strongly. In the air it is relatively easy to communicate along a line of sight, so UAVs can be part of interconnected networks able to relay huge amounts of data. Fortunately, Earth's atmosphere readily propagates most radio frequencies up to about 100 GHz (gigahertz), even through heavy rain. For example, it is possible, using small (~8 in.) directional antennas, to exchange about 10 Gbps (gigabits per second) between high-altitude UAVs and surface stations, over typical slant ranges, using only 1 W of radiated power. Two UAVs can be separated by 500 km (~300 mi) and still maintain a line of sight above bad weather. Even with these theoretical data rates reduced by a factor of 100 to give an antijamming margin, a network of UAVs can create a densely interconnected communications grid that provides service that is the equivalent of high-definition television (HDTV) quality between surface units in the battlespace, the UAV network, and the fleet offshore.

A low-bandwidth system of small, omnidirectional antennas, similar to cellular telephone systems, can service requests for access to the high-data-rate network as well as provide limited service to ground units through foliage and other background clutter. While it is difficult to provide reasonable communications to ground units (including UGVs) without aerial relays, such a UAV network can provide high bandwidth to surface units. Most current UUV missions require that the vehicle periodically raise a small device to the surface to get a fix from GPS. At such times the UUVs could tie in to the UAV network to exchange large amounts of data with human operators and offboard automated systems.

Communications underwater are extremely challenging. The most capable systems offer only about 10 kbps (kilobits per second), using acoustic communications that have very high signature for detection and localization by the adversary.

While the Office of the Secretary of Defense (OSD) is moving aggressively to implement the Global Information Grid (GIG), a well-crafted Transformational Architecture for communications, significant issues remain to be fully addressed in developing the architecture for a workable network of highly mobile nodes. Fundamentally, the issue is to enable each node to maintain efficient routing and connectivity while different vehicles come in and out of local range and view of one another. This problem is one aspect of a larger challenge that includes airspace deconfliction (in a mix with piloted vehicles), AV resource allocation and tasking, the interoperability of different AV systems, and the management and distribution of information with different levels of security classification. While it is apparent that these issues are soluble, they are closely interrelated and need to be aggressively addressed as an integrated set of problems.

Endurance and range increase relatively slowly with the mass and cost of AVs (see Appendix B). For example, doubling the range and endurance of a typical AV having a modest fixed payload might be expected to increase its mass and cost by about a factor of 10. It is therefore very desirable to base AVs in support of naval operations on ships. Both the tremendous premium on range and endurance and the tremendous bandwidth of a theater-to-fleet, point-to-point AV communications network strongly favor ship basing for AV communications systems and provide a powerful underlying physical basis for the Navy doctrine of Sea Strike, Sea Shield, and Sea Basing to project sovereign military power.

As one example of the "art of the possible" for AVs in support of naval operations: it may be possible to develop a high-altitude, long-endurance, ship-based UAV having modest EO/IR ISR&T sensors and supporting multipoint communications relay that would be less expensive than the cost of shooting it down. As an "antenna farm," this vehicle would not be particularly stealthy, but shooting down a relatively small U.S. asset at high altitude is intrinsically difficult and very dangerous. Such a UAV might have a very small spot factor, or ship deck parking area. It could have a payload bay that supported expensive payloads such as large-aperture optical sensors or weather-penetrating imaging radars, or cheaper payloads such as extra fuel tanks or joint direct attack munitions (JDAMs), which are precision-guided bombs. Carrying such different types of payloads, these UAVs could act as decoys for one another so that an adversary would not know which were the high-value targets. When weather is a problem, these UAVs could drop expendable micro-UAVs (possibly just gliders) to perform final target identification as required for weapons-release authority.

Projected Autonomous Vehicle Capabilities

The AVs available today are the systems that are actually flying or floating or driving and that can be ordered on the basis of the manufacturing time as the time limit. The AVs that will be available tomorrow are the systems now in development, with their development funding being established, and incorporating technologies available now. The AVs that will be available farther into the future are systems for which technologies have been conceived but must be developed and then incorporated into the systems.

The Navy can speed up its acquisition and use of AVs by accelerating its procurement of some of today's AVs (those of its own choice) while taking maximal advantage of existing AVs and AV developments of the other military Services. This latter effort might take the form of assigning Navy personnel to joint programs in which they would gain experience as operators and planners for the UAVs of other Services (e.g., Global Hawk and Predator with the Air Force) in field operations for tasking and data exploitation. In some cases the Naval Services do not need their own organic AVs because capabilities exist in other national and theater systems. In other cases, as exemplified below, the Naval Services clearly do need their own organic AVs and should not be forced to violate sound system design principles (e.g., tight feedback control) by relying on other Services for a core capability.

The Navy has some unique requirements for AVs. UUVs are the obvious example of such naval-specific needs, but its requirements regarding UAVs are almost as unique, and need to be addressed directly in development. While the other Services have moved ahead in developing the basic elements of AV technologies, the Navy can benefit from these developments, adding to them unique naval requirements, including the capability of deck takeoff and landing, deck handling and operations, minimization of deck spot sizes, and attending to the premium for antenna real estate aboard ships. UAVs designed for land-based operation will not generally meet these requirements, and the expense and time spent attempting to modify and adapt them to shipboard application may not be justified or successful. Conversely, UAVs to be based on ships (carriers, destroyers, amphibious ships, and the Littoral Combat Ship) need to be defined and procured for persistent ISR, SEAD, strike, communications relay, and so on. The Joint Unmanned Combat Air System under advanced development by DARPA, the Air Force, and the Navy addresses some but not all of these issues. It is clear that a single vehicle cannot satisfy all of the requirements. Where appropriate, the Navy can benefit from other Services' developmental expenditures and lessons learned, reducing the cost of fielding its own UAVs. To make this process effective, the closest attention must be paid to proper system engineering based on the "whole" problem (including concept of operations, airspace deconfliction in mixed airspace, mobile networking and interoperability, launch and recovery, and staffing and logistics support).

Combinations of Short-, Medium-, and Long-Range Sensing

As previously mentioned, for ISR&T imaging, image quality and coverage are determined by a relatively simple set of physical and optical rules. The farther one wishes to see, the larger the aperture (typically the lens diameter) required. This general principle applies and scales to all wavelengths, including imaging radars (which also have a power component in the scaling parameters). For the detection and classification of a target, a minimum amount of information is required, which in turn places requirements on the imaging system. For example, it is generally accepted that to classify a target (e.g., to determine whether a vehicle on the ground is wheeled or tracked), an image must have 16 resolution elements (pixels) across the narrowest dimension of the target. This image quality typically provides about 90 percent correct classification. From high altitude, a high-quality, large-aperture imaging system is required. From a lower altitude, smaller apertures, and therefore a lighter-weight and lower-cost system, can be used.

One effective operational combination is for ISR&T imaging to have a high-altitude detector/classifier cue a lower-altitude "examiner" to perform recognition and possibly identification. Since some lower-resolution radars can image through clouds whereas higher-resolution optical imagers do best in clearer air, this combination can be very effective. In practice this system solution requires that the lower-altitude UAV be able to get to the indicated location quickly, which can be a problem for low and slow ISR UAVs if they are not deployed nearby. As previously mentioned, one apparently attractive option is to have a larger, high-altitude ISR&T UAV deploy a small, expendable, low-altitude UAV to get close-up images, even in clouds or fog, for final target confirmation and human weapons-release authority as required by normal rules of engagement. Such systems have been successfully used in experiments in which the small "Finder" UAV developed by the Naval Research Laboratory was deployed from a long-endurance Predator UAV.

Sensing includes nonimaging methods such as electromagnetic sensing (EMS), SIGINT, and other means of cueing for imaging systems. One example is a payload that includes EMS (for detecting the carrier signal of a threat radar) that cues the imager to look in the source direction and send back the image and the location of a threat radar.

In summary, higher-quality, broader-coverage imagery requires larger aircraft at higher altitudes, while smaller imaging systems can be used at lower altitudes to give extremely high resolution over small areas. In UUV optical imaging applications, short ranges are normal, being limited by the low optical transparency of the water. To remedy this limitation, imaging sonars are often used; with these as with other sensors and for the same physical reasons (wave properties), larger apertures are required to give acceptable resolution.

Manned and Unmanned Systems Working Together

While AVs are valuable as independent mission assets, one of the most promising modes of operation for AVs is to enhance manned mission capability by operating as wingman or adjunct. The Army, through the Future Combat System (FCS) program, has a doctrine indicating that increased awareness of enemy positions and numbers (information dominance) will allow the defeat of an enemy that has more units and heavier armor. According to this doctrine, FCS forces fire from cover, avoid battle, bypass enemy forces, and avoid ambush even as the FCS forces are just beginning to build up. The information dominance enabling such actions will be provided by UAVs and UGVs working in concert with manned systems.

There are few or no well-thought-out concepts of operations for mixed manned and AV operations. Constructive, live, and virtual simulation could play an important role here. The Marine Corps can take full advantage of these developments where appropriate. It is noted that the Marine Corps has been one of the most visionary organizations with regard to AVs, supporting R&D efforts going back more than 20 years. The Marines developed the hand-launched UAV Dragon Eye and the small, teleoperated UGV Dragon Runner that have yielded important experience and lessons learned in Operation Iraqi Freedom.

Defeating the larger enemy while using assets that can be quickly inserted by a few C-130s (as envisioned by FCS) means optimizing each component, including armored vehicle size, the number of personnel, and the mix of AVs. This same logic can be applied to the provision of forces and components arriving by ship and to the reviewing and optimizing of the mix of assets, with AVs included.

It needs to be noted that this report does not address in any great detail the following questions: (1) How does the performance of an autonomous vehicle system degrade owing to communications bandwidth and latency if a human crew is put offboard? (2) Can fewer humans be used offboard than would be used for the same number of manned aircraft (e.g., can a single, human crew "pilot" multiple AVs and still be highly effective)? Briefly, the answers to these questions are that the bandwidth currently needed to provide the remote human operator with the necessary situation awareness is very large. However, providing this bandwidth is actually not difficult based on physical law, as discussed in Appendix B. Automated systems can handle aircraft controls and communications latencies at least as well as humans, so it is possible to make UAVs and UGVs (communicating through a UAV network) highly capable by putting the crew offboard. The communications issues that constrain interoperability between AV systems are discussed in Chapter 7 in the subsection entitled "Communications Issues as Constraining Factors on Interoperability." What is not straightforward is the question of having a single crew control many vehicles simultaneously—because during periods of peak operational tempo, the performance of all such systems are limited primarily by the ability of the crew to sense and assimilate information, even if all of the necessary information is delivered from the AV to the remote crew. Huge advances in computing and algorithms will be required to change this latter fact. An alternative approach to having a single crew pilot multiple vehicles is to time-share less than one crew per vehicle, allocating them only to those vehicles where the operational tempo is greatest and accepting the losses that result. This approach may be cost-efficient if the costs of the AVs can be made relatively low compared with the operational costs of maintaining a large number of crews. There is little specific work on how operator performance degrades with increased operations tempo and mission complexity, but psychological research suggests limits to performance, and more such research is required. The operator-to-vehicle ratio as a function of operations tempo and mission complexity is not known, but estimates for UGVs range from 2:1 to 1:5. Refining operator-to-vehicle ratio as a function of operations tempo and mission is important, and more research is needed.[18]

[18]Private communications with Clinton W. Kelly, Science Applications International Corporation, May 2004.

3

Autonomy Technology: Capabilities and Potential

Autonomous vehicles (AVs) have demonstrated that they can significantly increase the operational capabilities of modern armed forces, and it is evident that they will become an even more important element of warfighting capability in the future. This chapter discusses the state of the art of autonomous systems, examines some promising autonomy technology that will be available in the near future, and identifies some shortfalls in autonomy capability that need to be alleviated. The chapter goes on to explore the level of autonomy as a design choice and autonomy technologies.

TODAY'S AUTONOMOUS VEHICLE SYSTEMS

Types of Systems

There are three types of autonomous vehicle systems: scripted, supervised, and intelligent. *Scripted autonomous systems* use a preplanned script with embedded physical models to accomplish the intended mission objective. Examples of these systems include smart bombs and guided weapons. Such systems can be generally described as "point, fire, and forget" systems that have no human interaction after they are deployed.

Supervised autonomous systems automate some or all of the functions of planning, sensing, monitoring, and networking to carry out the activities associated with an autonomous vehicle, while using the cognitive abilities of human operators via a communications link to make decisions, perceive the meaning of sensor data, diagnose problems, and collaborate with other systems. Most conventional autonomous vehicles and their controlling elements form an autonomous system that fall into this category.

Intelligent autonomous systems use intelligent autonomy technology to embed attributes of human intelligence in the software of autonomous vehicles and their controlling elements. This intelligent autonomy software does the following: (1) it makes decisions, given a set of (generally automated) planned options; (2) it perceives and interprets the meaning of sensed information; (3) it diagnoses vehicle, system, or mission-level problems detected through monitoring; and (4) it collaborates with other systems using communications networks and protocols.

This major section discusses technologies relating to supervised and intelligent autonomous systems. The systems and technology associated with such systems generally reside in the Mission Management System or Command and Control System elements of an the autonomous system (see Figure 3.1), while the actions that implement higher-level decisions are done today (generally autonomously) by the Vehicle Management System (VMS) (e.g., by autopilots). Following is a descriptive list of the various systems that comprise the elements of an AV system.

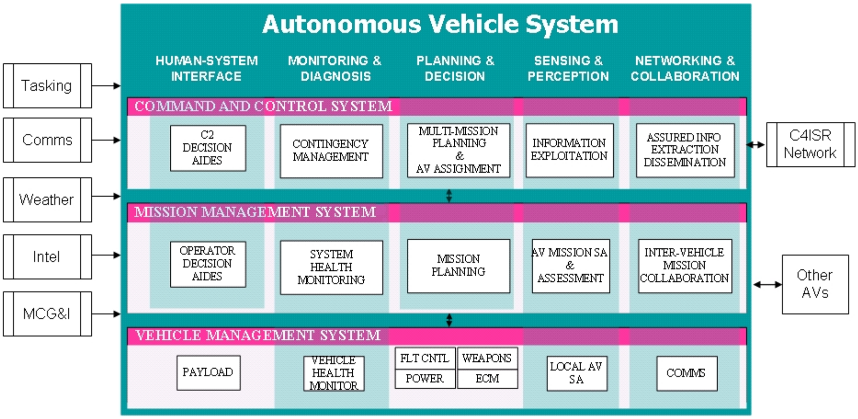

FIGURE 3.1 The elements of an autonomous vehicle system. NOTE: C2, command and control; C4ISR, command, control, communications, computers, intelligence, surveillance, and reconnaissance; MCG&I, mapping, charting, geodesy, and imagery; ECM, electronic countermeasures; FLT CNTL, flight control; SA, situation awareness.

- *Planning and Decision.* Planning and decision is the process of developing a sequence of actions capable of achieving AV mission goals or activity goals, given the state of the world. The Planning and Decision System dynamically plans and commands functions within the VMS to carry out mission activities, given situation-awareness information from the Sensing and Perception System and self-awareness information from the Monitoring and Diagnosis System. A plan diagnosis assesses the need to replan on the basis of situational changes derived from updated information. Planning and decision systems often use human-machine collaboration to complete their tasks.
- *Sensing and Perception.* The Sensing and Perception System collects, fuses, and interprets sensor data from local sensors and from the Networking and Collaboration System, which receives data from external sources. This information is used to develop a mission-relevant picture or digital map representation of the current mission situation for use by the Planning and Decision System. The digital map, which is dynamically updated, contains information on the location of the AV with respect to all known threats, targets, terrain, obstacles, and friendly forces. Sensing and perception systems often use human-machine collaboration to complete their tasks.
- *Monitoring and Diagnosis.* The Monitoring and Diagnosis System collects, fuses, and interprets sensor information relating to the health of the AV. Its responsibilities include the fault detection and isolation (FDI) of system, subsystem, or component failures. FDI helps prevent loss of the AV resulting from system failures and increases the probability of mission success if vehicle systems can be reconfigured during a mission using redundant capability. This system may also include sensors to monitor health trends in key subsystems in order to enable preventive maintenance and prognostication of future failures.
- *Networking and Collaboration.* The Networking and Collaboration System manages the use of data links, frequencies, and information content for purposes of collaboration. Collaboration involves the sharing of information with other autonomous or manned vehicles operating as a team or with other vehicles operating in the same space. The types of information shared are, for example, navigation state for collision avoidance, pop-up threat locations, new target locations or targets of opportunity, and vehicle mission plans or plan fragments required to support the collaboration.
- *Human-System Interface.* The Human-System Interface System is an extremely important element of an autonomous system. Even in highly autonomous systems, humans are required to provide high-level objectives, set rules of engagement, supply operational constraints, and support launch-and-recovery operations. Humans are also needed by autonomous systems to help interpret sensor information, monitor systems and diagnose problems, coordinate mission time lines, manage consumables and other resources, and authorize the use of weapons or other mission activities.

- *Other Autonomous Behaviors.* Some VMS functions contain autonomous modes or behaviors that can be commanded and controlled by the Planning and Decision System. A common example is an autopilot function of the Guidance, Navigation, and Control System, which may have multiple modes depending on the flight phase, flight conditions, or operating environment.

The State of the Art

Contemporary autonomous systems employ a wide range of autonomy technology, depending on the vehicle domain (i.e., air, ground, sea) and the operating requirements of the system. The following subsections present a brief summary of the current state of the art for the autonomy capability areas developed in the preceding section, "Types of Systems."

Planning and Decision

The general problem of planning and decision has been addressed in operations research and artificial intelligence for more than 30 years, with the research addressing increasingly complex formulations of the planning problem. Path planning or route planning is commonly available today in all domains. Autonomous mission planning, which involves the development of plans to achieve mission goals, is primarily accomplished through automated tools that are defined premission and subsequently executed. The Navy's Portable Flight Planning System (PFPS) for aircraft is an example of a planning system in use today. The PFPS and the developmental Joint Mission Planning System (JMPS) are excellent premission flight-planning systems with large databases of information to support high-fidelity flight planning; however, both lack the ability to rapidly accommodate evolving mission events through dynamic planning.

The modification of mission plans owing to the occurrence of unanticipated events is heavily dependent on "humans in the loop" for all autonomous vehicle domains. Dynamic mission planning that enables autonomous mission replanning to take into account unanticipated events is not common today, although capabilities on unmanned undersea vehicles (UUVs) have advanced the state of the art in this area. Dynamic mission-level planning is also a current thrust in the Office of Naval Research's (ONR's) Maritime Reconnaissance Demonstration (MRD) Program and its Intelligent Autonomy Program (e.g., the Risk-Aware, Mixed-Initiative Dynamic Replanning Program).

Some collaborative multivehicle planning development, at a low level of autonomy, has also been done in the past for unmanned aerial vehicles (UAVs) at ONR in the Uninhabited Combat Air Vehicle (UCAV) Demonstrations Program and at the Air Force Research Laboratory (AFRL) in the Cooperative Manned/Unmanned Systems Program. Both programs used a single ground station to control a team of UAVs that shared Global Positioning System (GPS) navigation solutions for route deconfliction.

Finally, the National Aeronautics and Space Administration's (NASA's) Remote Agent Experiment was executed for several days onboard the NASA Deep Space One mission,[1] representing a significant demonstration of autonomy in space operations. This mission emphasized planning and decision capabilities to maintain the spacecraft in a desired internal state by planning time lines of activities, sequencing lower-level steps together to achieve higher-level goals, and executing plans in a reliable fashion. The system made use of probabilistic models of the subsystem hardware to detect and diagnose failures and replan the mission activities. Temporal planners, such as the Remote Agent Planner, can take hours to generate plans of large size unless hand-coded heuristics are provided, but alternatives are under development to improve searches for feasible time bounds of mission activities when generating mission time lines.

Sensing and Perception

Sensing and perception technology in today's fielded systems is primarily used for AV navigation and avoidance of terrain hazards. Most AVs employ GPS-aided inertial navigation systems, although UUVs also employ Doppler velocity logs or other velocity correction sensors to aid the inertial system for navigation. Terrain sensing—using sonar for UUV bottom following and unmanned ground vehicle (UGV) behaviors such as wall following or road following—is also in use today. Cruise missiles employ terrain-matching and scene-matching technology that may have application for some UAV missions.

Obstacle-detection technologies have also been a research focus over the past decade, with emphasis on AV operations in complex terrain. This capability is particularly important for off-road UGV operations, littoral UUV operations, urban environment UAV operations, and undercanopy UAV applications. Obstacle-detection systems use a variety of sensors, including electro-optic cameras (stereo and mono), infrared cameras, ultrawideband radars, sonars, and light detection and ranging (LIDAR). The ONR Maritime Reconnaissance Demonstration Program is using bathymetry maps and forward-looking sonar to perform obstacle avoidance. The Defense Advanced Research Projects Agency (DARPA)/Army Demonstration III Program employed LIDAR and stereo cameras to build a three-dimensional map of the vehicle's immediate surroundings, which was then used to plan local paths that move toward a goal while avoiding the obstacles.

Autonomous systems that detect, classify, and identify targets or threats are limited primarily to the UUV domain, although manned aircraft also include

[1]For further information, see the Web site <http://nmp.jpl.nasa.gov/ds1/>. Last accessed on April 5,

technologies to support the pilot that could be utilized for UAVs. The creation of situation-awareness maps is also rare today, except in UUVs used for mapping the location of underwater mines, which was done in the mid-1990s in the DARPA Autonomous Minehunting and Mapping Technologies Program and is a part of the Remote Environmental Monitoring Unit System (REMUS), Remote Minehunting System (RMS), and Long-range Mine Reconnaissance System (LMRS). The ONR Maritime Reconnaissance Demonstration Program (part of the Autonomous Operations Future Naval Capability (FNC)) is using a situation-awareness sensor suite, including communications intelligence (COMINT), electronic intelligence (ELINT), and video to detect, map, and avoid surface threats. A *Virginia*-class submarine (VSSN) provides mission command and control for the UUV. The MRD UUV transmits the threat type, location, and bearing to the VSSN, which provides the new threat information to update the battlegroup's common operational picture. The VSSN also provides target-identification objectives to the MRD UUV for searching out and verifying surface targets. This capability was demonstrated in April 2003 during Fleet Battle Experiment Kilo.

Much work has been done and is still ongoing in the area of automatic target-recognition and threat-detection systems. Many techniques have been explored for a variety of sensors, but most methods are limited in their capability owing to unfavorable lighting conditions, weather, and viewing geometry, or obscurations such as foliage or terrain. Still, it is likely that some of this research will be used to field automatic target-cueing systems in the near term. These systems will not likely be fully autonomous, but will help either to increase operations tempo or to reduce operator workload.

Monitoring and Diagnosis

As described above, monitoring and diagnosis systems are used to detect and isolate failures within AV subsystems. The monitoring and diagnosis systems in use today primarily employ built-in test equipment to sense the malfunctioning of subsystems and equipment. This information is generally used for diagnostics and maintenance support, but is also infrequently used to support the reconfiguration of the autonomous system or the replanning of the mission, particularly in UUVs. System reconfiguration and mission replanning typically require redundant systems to be available onboard the AV. Some UUVs today also make use of triplex or quad-redundant, fault-tolerant computers that choose among input and output signals to detect and isolate failures. This technology, more common in manned systems, is infrequently used today for autonomous vehicles. DARPA's Autonomous Minehunting and Mapping Technologies Program was an example of the use of quad-redundant, fault-tolerant computing in a UUV.

Analytical redundancy—which makes use of mathematical models of hardware subsystems to provide estimates of the expected sensor measurements or vehicle responses for failure detection and isolation—is employed in manned systems, but is infrequently used in autonomous vehicles today.

Networking and Collaboration

Most of today's AVs do not directly or autonomously collaborate with other manned or unmanned vehicles. Those that do primarily exchange navigation state to permit collision avoidance with other vehicles and often do so through ground control stations with human intervention. Collaboration among vehicles is largely accomplished by the operators controlling the mission.

Research on networking and collaboration for AVs has increased in recent years, with programs such as DARPA's Mobile Autonomous Robot Software (MARS)[2] and Software for Distributed Robotics (SDR).[3] These programs are researching soft computing, initiative learning, coordinated control, and networking and communications autonomy technology to enable future collaborative robot capabilities.

LEVELS OF AUTONOMY

In order to classify systems for purposes of comparison, it is useful to identify the level of autonomy (LOA) that systems exhibit. Defining LOA in a simple, useable form has proven to be a difficult task. As yet, no single scale expressing LOAs has been found acceptable across the broad range of users. Intuitively, it seems that the mix of human and machine capabilities to be found in any particular system (or vehicle) implementation could be appropriately characterized by position along a linear axis with manual operation at one end and fully autonomous operation at the other. The many such attempts to define simple LOAs in this fashion have resulted in scales with differing numbers and definitions of the intermediate levels. These scales are summarized below, together with an expanded view of LOA as recommended by the committee.

Autonomy Scales Defined by the Department of Defense

One level-of-autonomy scale, created by the DARPA/U.S. Air Force (USAF)/ Boeing X-45 program team, represents a rather high-level, broad-brush view of autonomy, with only four levels. This scale is presented in Box 3.1.

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[2]For additional information, see the Web site <http://www.darpa.mil/ipto/programs/mars/vision.htm>. Last accessed on April 5, 2004.

[3]For additional information, see the Web site <http://www.darpa.mil/ipto/programs/sdr/vision.htm>. Last accessed on April 5, 2004.

BOX 3.1
Levels of Autonomy as Defined by the Uninhabited Combat Air Vehicle Program

Level 1 (Manual Operation)
- The human operator directs and controls all mission functions.
- The vehicle still flies autonomously.

Level 2 (Management by Consent)
- The system automatically recommends actions for selected functions.
- The system prompts the operator at key points for information or decisions.
- Today's autonomous vehicles operate at this level.

Level 3 (Management by Exception)
- The system automatically executes mission-related functions when response times are too short for operator intervention.
- The operator is alerted to function progress.
- The operator may override or alter parameters and cancel or redirect actions within defined time lines.
- Exceptions are brought to the operator's attention for decisions.

Level 4 (Fully Autonomous)
- The system automatically executes mission-related functions when response times are too short for operator intervention.
- The operator is alerted to function progress.

Another, more detailed LOA scale, with 10 levels, was created by the Army for the Future Combat System (FCS) Program. That scale is shown in Table 3.1. Still other LOA scales similar to these have been created by other programs in connection with developing autonomy technology or autonomous vehicles. These include the Air Force's autonomous control levels, which are defined for the observe-orient-decide-act (OODA) loop.[4] The OODA loop defines different LOAs for each of the four primitive elements of closed-loop autonomy, namely—observe, orient, decide, and act.

The intermediate levels of one scale often seem to be unrelated to those of another, so a one-to-one correspondence between the levels defined by different scales is difficult to establish. The source of this confusion lies in the one-dimensional nature of most attempted definitions of LOAs, as well as in the

[4]For additional information, see the Web site <http://www.adtdl.army.mil/cgi-bin/atdl.dll/fm/6-0/appa.htm>. Last accessed on April 5, 2004.

differing focus of each of the groups defining the LOAs. The application of autonomy concepts and technology to a system is inherently a complex issue, with several degrees of freedom that must be addressed. Thus, it is impossible to characterize the implemented degree of autonomy completely with a single number.

An Expanded View of Level of Autonomy

The main expectation for Navy and Marine Corps autonomous vehicles is that they be able to carry out mission goals reliably, effectively, and affordably with an appropriate level of independence from human involvement. However, in practice it is difficult to assign a single level of autonomy to any AV. This is largely because AVs and their controlling systems are designed to perform complex missions made up of many activities, each of which may be implemented with a different level of autonomy. This fact implies that the notion of *complexity* must also be considered when assigning an LOA to an AV.

This section proposes a new view of level of autonomy, which is hereafter called *the level of mission autonomy*. As described below, mission autonomy is made up of two degrees of freedom—*mission complexity* and *degree of autonomy*. "Mission complexity" captures the number of functional mission capabilities inherent in any given system or the number of different mission activities that can be implemented by the system, independent of whether they are accomplished autonomously or not. "Degree of autonomy" captures the amount of autonomy used to implement any specific mission activity or functional capability.

Mission complexity, the first degree of freedom, is not to be confused with *system complexity*, which increases as the number and variety of system elements (e.g., vehicles, operators, processors, data links, sensors, databases, power bases, and so on) become greater and as the level of predictability of the system decreases. System complexity results, in part, from the selection of mission autonomy requirements.

To further elaborate on mission complexity, it is useful to view it in the context of an autonomous vehicle mission. A mission is a hierarchical collection of mission activities that are sequenced to accomplish mission goals. High-level activities (i.e., mission phases such as launch, ingress, operations, egress, and recovery) are broken down into subordinate activities, which are themselves further decomposed into primitive activities. Each mission activity can be accomplished by a different mix of human and/or machine collaboration. The human involvement in the mission can be categorized in terms of control and authorization, coordination, and intelligence, as the examples in Box 3.2 suggest.

The number of mission activity levels (e.g., high, medium, low), the number of mission activities within each level, and the degree of human-equivalent functionality (e.g., intelligence) required for each are design choices that, once made, define the complexity of the AV itself. Mission complexity is then characterized by the number of functional mission capabilities that can be performed by the

TABLE 3.1 Levels of Autonomy in the Army Scale for the Future Combat System

Level	Level Description	Observation Perception and Situation Awareness	Decision-Making Ability	Capability	Example
1	Remote control	Driving sensors	None	Remote operator steering commands	Basic teleoperation
2	Remote control with vehicle state knowledge	Local pose	Reporting of basic health and state of vehicle	Remote operator steering commands, using vehicle state knowledge	Teleoperation with operator knowledge of vehicle pose situation awareness
3	External preplanned mission	World model database—basic perception	Autonomous Navigation System (ANS)-commanded steering based on externally planned path	Basic path following, with operator help	Close path following intelligent teleoperation
4	Knowledge of local and planned path environment	Perception sensor suite	Local plan/replan—world model correlation with local perception	Robust leader-follower with operator help	Remote path following—convoying
5	Hazard avoidance or negotiation	Local perception correlated with world model database	Path planning based on hazard estimation	Basic open and rolling semiautonomous navigation, with significant operator intervention	Basic open and rolling terrain
6	Object detection, recognition, avoidance or negotiation	Local perception and world model database	Planning and negotiation of complex terrain and objects	Open, rolling terrain with obstacle negotiation, limited mobility speed, with some operator help	Robust, open, rolling terrain with obstacle negotiation

7	Fusion of local sensors and data	Local sensor fusion	Robust planning and negotiation of complex terrain, environmental conditions, hazards, and objects	Complex terrain with obstacle negotiation, limited mobility speed, and some operator help	Basic complex terrain
8	Cooperative operations	Data fusion of similar data among cooperative vehicles (such as UAVs)	Advanced decisions based on shared data from other similar vehicles	Robust, complex terrain with full mobility and speed. Autonomous coordinated group accomplishments of ANS goals with supervision	Robust, coordinated ANS operations in complex terrain
9	Collaborative operations	Fusion of ANS and reconnaissance, surveillance, and target acquisition (RSTA) information among operational-force UGVs	Collaborative reasoning, planning, and execution	Accomplishment of mission objectives through collaborative planning and execution, with operator oversight	Autonomous mission accomplishment with differing individual goals and little supervision
10	Full autonomy	Data fusion from all participating battlefield assets	Total independence to plan and implement to meet defined objectives	Accomplishment of mission objectives through collaborative planning and execution, with operator oversight	Fully autonomous mission accomplishment with no supervision

SOURCE: LTC Warren O'Donell, USA, Office of the Assistant Secretary of the Navy (Acquisition, Logistics, and Technology), "Future Combat Systems Review," presentation to the committee, April 25, 2003.

BOX 3.2
Examples of Human Performance Capabilities in Autonomous Vehicle Missions

Control and Authorization
- Authorize activities
- Provide tasking orders
- Control the autonomous vehicle's path
- Monitor the autonomous vehicle's systems
- Disseminate information to users

Coordination
- Manage resources (i.e., vehicles, consumables, sensors)
- Generate time lines
- Generate subordinate tasking orders
- Communicate subsystem failures

Intelligence
- Interpret and exploit sensor data
- Develop situation awareness
- Plan mission activities
- Diagnose system failures

combined human-machine system. Functional capability is an amalgamation of human-machine capabilities embodied in the sensing, processing, ground system, and human operator/pilot capabilities. Examples of functional capability include launch, threat response, terrain following, weather avoidance, target search, target prosecution, and formation flight, to name just a few. Systems that are capable of implementing more functional mission capabilities (whether autonomous or not) are said to be more complex.

The second degree of freedom, which is largely independent of the first, is the degree of autonomy to be implemented for each of the mission activities. The degree of autonomy implemented at each mission level or in each activity can be chosen from a range of possibilities—from complete dependence on the human to complete independence from the human. Between these extremes, the degree of autonomy to be implemented is a design choice, subject to standard design trade-offs of such factors as performance, cost, and supportability.

It is clear then that no single number can precisely characterize the total autonomy content of the system implementation. As a result, the current Department of Defense (DOD)-defined autonomy scales are at best qualitative, and strongly dependent on the aspect of the mission (and system) that has been chosen as a focus.

Today's Autonomous Vehicles

It is useful to consider the current status of existing AV systems plotted against the two orthogonal axes of degree of autonomy and mission complexity. Together, these two degrees of freedom represent the level of mission autonomy for an AV as discussed in the preceding section. The axis labeled "degree of autonomy" (or percentage time without operator intervention) can be thought of as roughly representing the percentage of required mission capabilities that are handled by the system itself without direct, real-time human interaction. Accordingly, this axis is labeled with percentages—0 percent represents a situation in which the human has total control of all aspects,[5] while 100 percent represents the totally autonomous, completely hands-off system with no human real-time control or interactions at all. For the axis labeled "mission complexity" (involves more uncertainty, requires more system adaptability), a highly simplified scale is used, with three bins representing the main levels (low, medium, and high). With these crude definitions, the parameters for several well-known current AV systems were estimated and are plotted on Figure 3.2. Also indicated are two examples of the extreme possibilities—a manned fighter aircraft, which has high mission complexity with a small amount of autonomous functionality at the lowest levels (e.g., autopilot), and a thermostat that is 100 percent autonomous but which performs only a very simple task.

It is interesting to note that several of the AVs currently developed or under development (i.e., Dragon Runner, Predator Fire Scout, Global Hawk, LMRS, multi-reconfigurable UUV (MRUUV), and so on) fall closely along a trend line suggesting almost 100 percent correlation of these two variables. That is, the more autonomy utilized, the more challenging the task (i.e., complexity) that can be undertaken, or vice versa. This observation suggests that current AV design practice is not treating the LOA as a design parameter to be traded off against various system performance criteria. Rather, it would appear that LOA is being interpreted as is implied by the several one-dimensional scales of autonomy, which assume precisely the correlation seen in Figure 3.2—that is, the more "autonomous" the system the more complicated the tasks it performs. It seems that the several one-dimensional scales of LOAs defined to date are in fact defined not along the "autonomy" axis, as suggested by the name "levels of autonomy," but more or less along the 45º line in the autonomy-complexity plane. This represents an implicit design choice that is probably not explicitly recognized by the AV development teams. Moving off this artificially constrained design path in the autonomy-complexity plane opens up a broad range of design

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[5] Somewhat unrealistic, as all hardware implementations have some low-level components that operate "automatically."

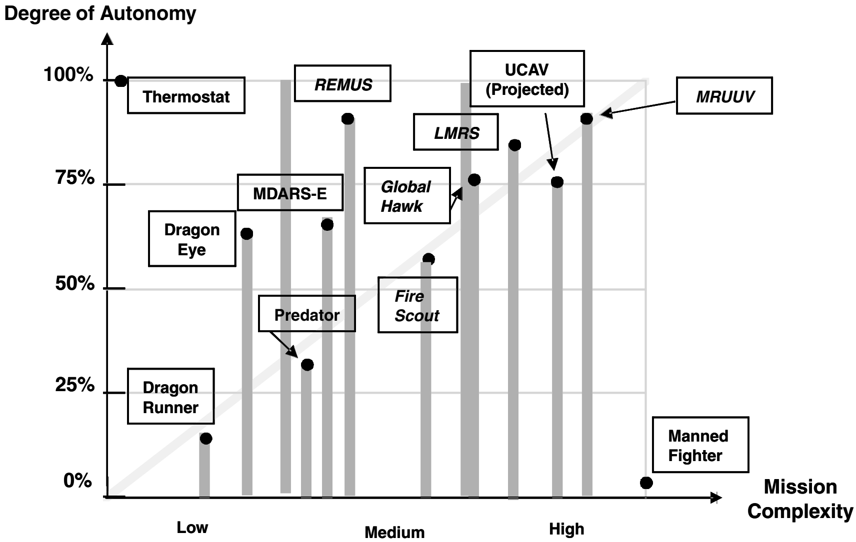

FIGURE 3.2 Mission autonomy in today's autonomous vehicles (AVs), based on estimated parameters for several current AV systems and two extreme possibilities (manned fighter and thermostat). NOTE: A list of acronyms is provided in Appendix D.

options that could greatly affect the overall merits of the final system implementation.

Figure 3.3 plots mission autonomy versus system complexity. "Mission autonomy" is defined here to be the product of mission complexity and the degree of autonomy, placed on a scale from 1 to 10, with 10 being a notional maximum level of mission autonomy. AVs with a high level of mission autonomy are those that simultaneously have a high mission complexity and a high degree of autonomy. It is apparent from this figure that for today's autonomous systems, higher mission autonomy typically results in higher system complexity. There are two reasons for this. First, autonomy capability often is distributed throughout the system and offboard the AV platforms. Second, the perception is that a higher level of autonomy results in less system predictability, which results in added complexity to provide more human oversight. It is expected that higher levels of mission autonomy will actually result in lower system complexity in future systems, as confidence in autonomy capability increases and as more autonomy capability is migrated onboard autonomous vehicles. An indication of such changes can be seen by the fact that UUVs tend to have less system complexity than UAVs have for the same level of mission autonomy. This is due in part to the higher degree of onboard

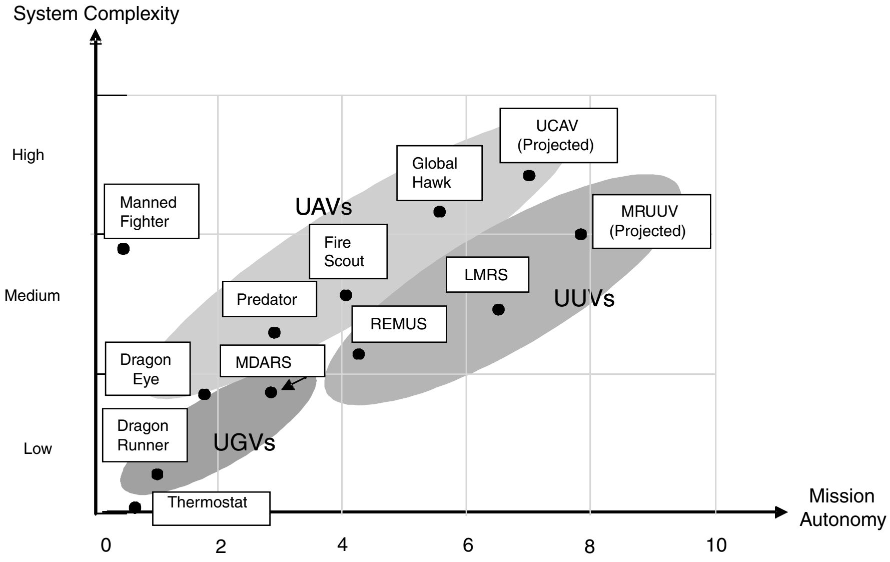

FIGURE 3.3 Relationship between mission autonomy and system complexity. "Mission autonomy" is defined here to be the product of mission complexity and the degree of autonomy, placed on a scale from 1 to 10, with 10 as the notional maximum. NOTE: A list of acronyms is provided in Appendix D.

autonomy required by UUVs to operate in the absence of communications with an operator. Operational speed and desired response time/consequences of failure would appear to result in increased complexity as well.

USING LEVEL OF MISSION AUTONOMY AS A DESIGN CHOICE

Autonomous vehicles have the potential to increase U.S. military operational capability significantly. They will become an even more important element of our warfighting capability in the future. As discussed in some depth below, advances in autonomy capability are the key to providing this enhanced warfighting capability. These advances will improve the mission effectiveness and affordability of these systems and increase their ability to survive in hostile, threat-dense environments. To realize the payback of increased autonomy, the Navy and Marine Corps can take aggressive steps to make this evolving capability integral to their future. This effort begins with taking the view that level of mission autonomy is a design choice that can be leveraged in up-front system trade-off studies to impact mission effectiveness, vehicle survivability, and system affordability. This section expands on this view and discusses some promising autonomy technology for the near future and some shortfalls in autonomy capability that will ultimately be needed to enable the Naval Services vision for Sea Power 21.

Trade-off Studies on Autonomous Vehicle Systems

The level of mission autonomy (as defined above in the subsection entitled "An Expanded View of Level of Autonomy") is a design choice that, when exploited through system trade-off studies, can be used to evaluate the pros and cons of various concepts of operation. This evaluation can be made by comparing the operational capability provided by one level of mission autonomy versus that provided by another. The incorporation of level of mission autonomy in the design trade space with other, more traditional design choices (e.g., vehicle performance, range, endurance, stealth, and shipboard operations) allows system designers to compare the relative merits of various levels of vehicle capability having various levels of autonomy. This comparison is done in terms of the ability of each to achieve the overall desired operational capability or to enable new capabilities. It should be emphasized that by including autonomy capability in the trade space, it is possible that the best mission capability, for a given cost of ownership, will be achieved through a high level of mission autonomy but with a modest vehicle capability. Such trade-off studies will be extremely useful to Navy and Marine Corps requirements developers and program managers in conceptualizing highly capable, yet cost-constrained, autonomous systems during program development. This approach allows the Navy to methodically sort the surfeit of available or emerging autonomy technologies in order to focus on developing beneficial system-level autonomy capabilities that result from the integration of a number of fundamental autonomy technologies.

Figure 3.4 provides an illustration of a trade-off study methodology for incorporating level of mission autonomy as a design choice. The methodology can be viewed as an iterative evaluation of concept of operations (CONOPS) and top-level mission and system requirements, given different design choices. The operational capabilities, enabled by a set of system design choices, are subsequently used to adjust the design choices, CONOPS, and requirements. Operational capabilities are metrics associated with the key goals of the program and might include, for example, items such as the number of targets detected and identified, the number of targets prosecuted, the probability of vehicle survivability against various threats, and the total cost of ownership for the system (i.e., nonrecurring development cost plus operations and support cost).

The vertical integration of autonomy for the AV's command-and-control system (C2S), mission management system (MMS), and vehicle management

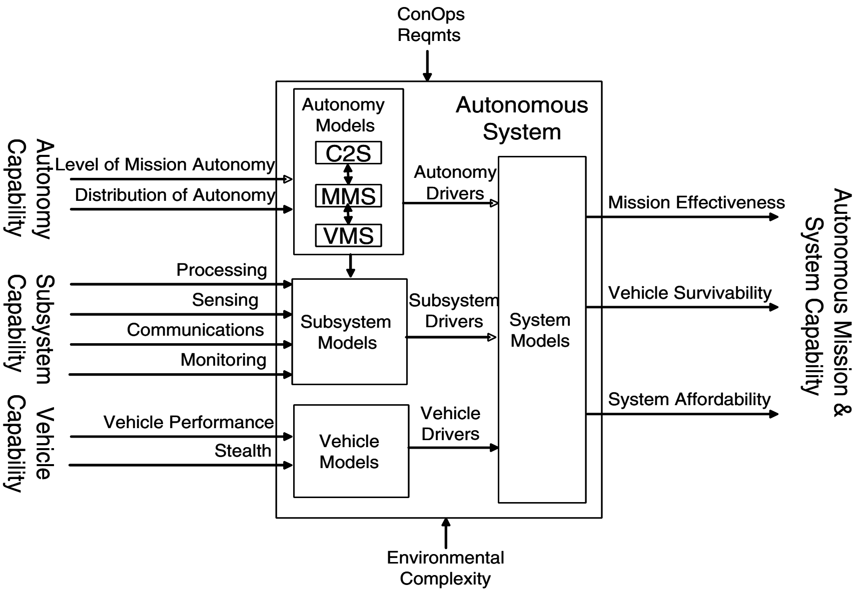

FIGURE 3.4 A trade-off study methodology incorporating level of mission autonomy as a design choice. NOTE: C2S, command-and-control system; MMS, mission management system; VMS, vehicle management system.

system (VMS) should be considered in this process. Vertical integration of autonomy for all levels of the system is particularly important if agile response to rapidly changing conditions is needed so as to achieve the desired operational capability. Vertical integration permits such things as route deconfliction with other vehicles operating in the same space, efficient exploitation and prosecution of targets of opportunity, and rapid response to system failures that impact mission objectives. It also permits retasking of the AV to accomplish new, higher-priority objectives, and it helps reduce "friendly fire" incidents through the better coordination of all controlled assets within the battlespace, including AVs.

The design of autonomous systems is traditionally accomplished by trading vehicle capability with subsystem capability to produce the desired mission or system capability for the given CONOPS and mission requirements. To fully realize the benefits described above, autonomy capability must become a part of this trade-off process.

The selection of autonomy capability associated with an autonomous system is intertwined with the selection of subsystem capability and vehicle capability.

For example, high levels of autonomy drive up processing, sensing, and monitoring requirements, while they relax communications requirements and needs for operating and support personnel. Conversely, low levels of autonomy drive communications requirements. The distribution of autonomy, both offboard and onboard the vehicle, is another degree of freedom often used by designers to mitigate constraints due to processing limitations, but this distribution drives communications system requirements.

Another key factor in the selection of autonomy capability is the complexity of the operating environment for the AV. Mission operations in complex environments (e.g., urban environments, under tree canopy, in littoral waters, or in forested regions) often require a high degree of autonomy because communications in such environments are intermittent at best. High levels of vehicle capability (e.g., sensing, perception, agility) may also be required in order to permit operations in these environments. This combination of high vehicle capability with high degree of autonomy makes the development of autonomous systems for these environments very challenging.

A final, additional factor in the selection of autonomy capability is the concern of robustness to the unanticipated events inherent in complex autonomous systems. Also of concern are emergent behaviors or system behaviors that unexpectedly occur during the execution of a mission owing to an implemented, autonomous decision-making capability.

Impacting Mission and Vehicle Characteristics

The primary value of autonomy—performing military missions without risking human life—hardly needs debate. But the use of autonomy has other benefits, too. The most obvious of these, which are discussed in more detail below, include faster response times for planning, decision making, perception, and diagnosis; and a lower overall labor cost for operations.

The goal of the trade-off study suggested in the previous section is to design an autonomous system with operational capabilities that enhance mission effectiveness, improve vehicle survivability, and reduce the total cost of ownership. It has long been accepted that parameters representing vehicle and subsystem capability can be traded so as to impact these three metrics. As shown in the following subsections, several key drivers associated with autonomy capability also have an influence on these metrics and therefore can be made part of the overall system design trade-offs.

Mission Effectiveness

Selecting higher levels of mission autonomy can enhance the overall mission effectiveness of an autonomous vehicle. The level of mission autonomy is a "knob" that can be used to tune several key drivers, each of which directly influences mission effectiveness. Some examples of key drivers are as follows:

- Time to plan and replan mission activities;
- Time to assimilate and correctly interpret onboard and offboard sensor information;
- Time to assimilate and correctly interpret command-and-control sensor information;
- Time to detect, isolate, and correctly assess the impact of system problems; and
- Distribution of mission objectives and tasks among collaborators.

The time that it takes to plan and replan mission activities owing to mismodeled or unmodeled system dynamics, system failures, pop-up threats, or other unanticipated events directly impacts the number of mission objectives that can be achieved in a given amount of mission time. Similarly, the time needed to assimilate and interpret onboard and offboard sensor data to create situation awareness directly impacts the number of achievable mission objectives. Overall, higher levels of autonomy support faster, closed-loop, dynamic planning cycles, which are composed of the closed-loop process of sensing, estimation, interpretation, and replanning. Faster dynamic planning cycles allow more mission objectives to be accomplished for a given vehicle endurance (however, the autonomy technology to enable this vision is not in place now). Low-endurance vehicles with fast planning cycles (a high level of autonomy) can be as effective as high-endurance vehicles with slow planning cycles (a low level of autonomy).

The probability of mission success is also determined by the ability of the system to adapt to system failures by detecting, isolating, and correctly assessing the impact of system problems on the mission. Reconfiguration of a redundant system can accommodate system failures, but it will result in lower system reliability and may result in degraded performance. The impact of both must be weighed, and a decision must be made about whether to continue the mission under such circumstances. The faster this decision can be made, the higher the overall probability of mission success for a given AV and the more effective the mission will be in terms of the number of objectives accomplished.

Finally, the distribution of autonomy among collaborators adds redundancy to the system, enables the redistribution of mission roles and objectives when system failures occur, and increases the number of mission objectives that can be achieved. Combined, these capabilities increase the probability of mission success.

Vehicle Survivability

Selecting higher levels of autonomy can improve autonomous vehicle survivability and provide better overall knowledge of the system's health. The level of mission autonomy is a design choice that can be used to tune several key drivers, each of which directly influences vehicle survivability. Following are some examples of key drivers:

- Time to assimilate and correctly interpret onboard threat information;
- Time to assimilate and correctly interpret command-and-control threat information;
- Time to assimilate and correctly interpret collaborator threat information;
- Time to plan the response to threats;
- Time to detect, isolate, and correctly assess the impact of system problems;
- Time to plan the response to system problems;
- The frequency and duration of communications; and
- Increased requirement for sensing and processing.

The speed of response of an AV to threats is a key to its survivability. The AV must detect, identify, classify, and then plan a response tactic to the threat. Every step that requires operator involvement through communications will slow the speed of response and increase the likelihood that the vehicle will be lost. The tactic employed will sometimes depend on the threat stage—that is, on whether the threat is in search mode, or in tracking mode, or has already engaged the AV with a weapon. Prompt early detection and classification allow a wider range of response tactics to be employed and a higher probability of the AV's surviving the threat. Threat awareness, and hence vehicle survivability, is further enhanced by the number of sources providing threat information to the AV. Threat awareness can be greatly improved if the AV can pull and assimilate threat information from its command-and-control network or from collaborating vehicles. When an AV does not have its own threat-detection equipment, collaborating vehicles can provide this threat awareness. System trade-off studies could evaluate concepts of operation that assume a distribution of autonomy among collaborating vehicles, since this may be the most cost-effective approach to implementing a particular mission capability.

The probability of the loss of a vehicle is directly impacted by the overall reliability of the autonomous system. System reliability is a dynamic metric determined by the probability of system failure occurrence (the failure rate), the probability of detecting and isolating a system failure when it occurs (the coverage rate), and the ability to accommodate the failure through reconfiguration. System failure rates can be lowered through system architecture design, the use of higher-quality parts, and changing out degraded subsystems or components detected through vehicle health monitoring and prognostication technology (requiring a higher level of autonomy). Coverage rates can be improved through the use of higher levels of autonomy that make use of analytical redundancy (e.g., hypothesis testing, detection filtering, and estimation). Autonomous reconfiguration of a redundant system can accommodate system failures if those failures can be quickly detected and isolated. Overall, rapid failure detection, isolation, and accommodation increase vehicle survivability, as does the ability to autonomously monitor and predict future failures or the need for subsystem maintenance.

Finally, higher levels of autonomy mean less-frequent and shorter-duration communications between the operators and the AVs they control. The result is a reduction in overall signature, allowing the AVs to operate more covertly.

The improvements gained in mission effectiveness and vehicle survivability through increased levels of autonomy come at the expense of increased sensing and processing requirements. These requirements may indirectly reduce the vehicle's survivability owing to lower vehicle performance, a larger visible signature, and a larger radar cross-section. This problem highlights the need to include mission workload, subsystem, and vehicle models in the up-front trade-off studies. The distribution of autonomy through collaboration and networking reduces the sensing and processing requirements for any given vehicle, which reduces the impact of these indirect influences on vehicle survivability. This approach is analogous to the wingman or fighter escort approach used for some manned aircraft missions.

System Affordability

Selecting higher levels of mission autonomy can reduce the total cost of ownership for an autonomous vehicle. The level of mission autonomy can be used to optimize several key drivers, each of which directly influences system affordability through reduced costs for life-cycle operations and support (O&S). However, increased autonomy comes with an attendant increase in the cost of system development. This latter cost must be weighed in system trade-offs against the reduced O&S costs when selecting a level of mission autonomy, as shown in Figure 3.5. In this figure, it is assumed that as levels of autonomy increase, there is a diminishing effect on their ability to reduce O&S cost, while these same levels of mission autonomy come with an increasing rate of development cost (including science and technology investments). The specific shapes of these curves will be domain-, mission-, and system-dependent, however, and therefore are an important element of the system trade-offs. Nonetheless, there is some optimal level of autonomy for each mission scenario.

Some examples of the key autonomy drivers affecting system affordability are as follows:

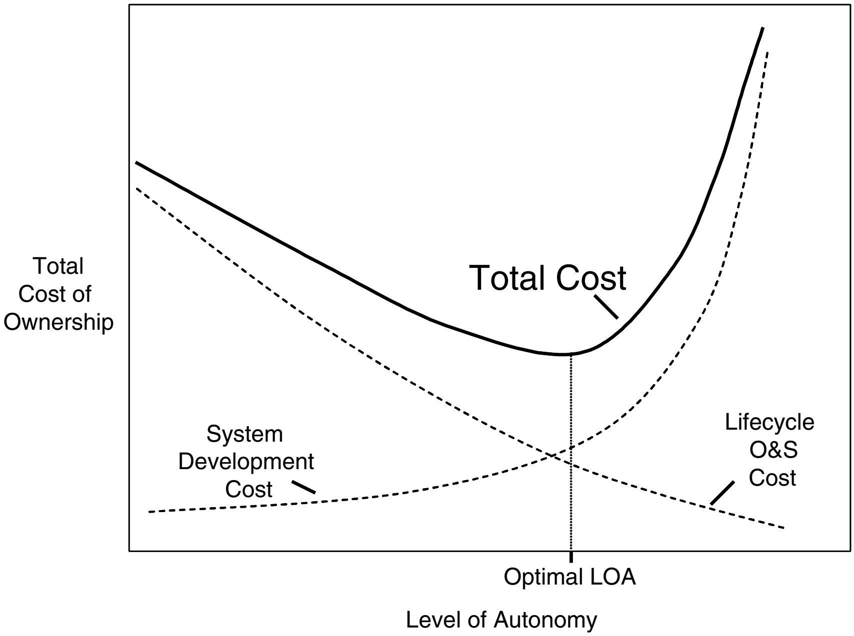

FIGURE 3.5 An example of the trade-offs of development cost versus life-cycle operations and support (O&S) cost for an autonomous vehicle.

- Improved mission effectiveness,
- Improved vehicle survivability and system reliability,
- Reduced requirement for operator and command-and-control support,
- Reduced requirement for maintenance support, and
- Increased system development cost.

Improved mission effectiveness will improve the unit cost per mission objective achieved (e.g., the cost per target detected or destroyed), although this cost must be traded against the increased development cost to achieve the improved mission effectiveness. Improved vehicle survivability reduces the number of vehicles to be procured or the rate of vehicle production. This difference will need to be balanced by the expected attrition rate of the AV, since it may be called on to operate in higher-risk operations than manned vehicles would be.

The increases in level of mission autonomy that were mentioned previously as a way to improve mission effectiveness and vehicle survivability also reduce operator and maintenance staff workloads and therefore reduce the overall O&S cost for the system, although the training cost element for operators and maintenance may increase. Even given these considerations, the level of improvements indicated are not the only reasons to increase autonomy capability. Higher levels of autonomy will in general reduce O&S costs for sensor interpretation, system-failure monitoring, problem diagnosis, and mission planning, even when the increased autonomy does not impact mission effectiveness or vehicle survivability. Similarly, higher levels of mission autonomy for system health monitoring reduce the maintenance and support staff workload needed to achieve a given level of system reliability. More capable AVs also reduce the workload needed of their command-and-control systems.

Finally, increased levels of autonomy *may* result in increased costs for system development and training, or they may simply result in a redistribution of cost from vehicle development to autonomy subsystem development. As noted above: It should be emphasized that by including autonomy capability in the trade space, it is possible that the best mission capability, for a given cost of ownership, will be achieved through a high level of mission autonomy, but with a modest vehicle capability. A corollary to this statement is that no more autonomy need be included than that required to do the task: for example—a cruise missile is smart enough to do its job.

AUTONOMY TECHNOLOGY

It is a daunting challenge for a vehicle to operate autonomously in a complex, threat-filled environment. The vehicle must be able to form plans to achieve its goals, plan its motion so as to reach objectives while avoiding threats, sense its environment in order to detect unanticipated threats and opportunities and respond to them in a timely fashion, monitor its own actions to make sure that its plans are in fact making progress toward its goals, monitor the health status and capabilities of its subsystems, and modify its plans when unanticipated events occur. Ideally, the AV must be capable of interacting collaboratively with other vehicles, human commanders, and command-and-control systems.

This section explores promising autonomy technology currently under development within the DOD and identifies the key technologies needed to achieve the DOD's vision as expressed in the 2001 Quadrennial Defense Review[6] and in the Navy's Sea Power 21.[7] Achieving the operational goals comprising these visions will depend upon several key operational capabilities, each of which requires advancements in autonomy capability to fully enable the attainment of the visions. These capabilities include the following:

[6]Donald H. Rumsfeld, Secretary of Defense. 2001. *Quadrennial Defense Review Report,* U.S. Government Printing Office, Washington, D.C., September 30. Available online at <http://www.defenselink.mil/pubs/qdr2001.pdf>. Accessed on May 13, 2005.

[7]ADM Vern Clark, USN. 2002. "Sea Power 21: Projecting Decisive Joint Capabilities," *U.S. Naval Institute Proceedings*, Vol. 128, No. 10, pp. 32-41.

- AV shipboard operations (e.g., UUV or unmanned surface vehicle (USV) launch and recovery, UAV parking onboard carriers);
- AV operations in threat-dense environments;
- AV operations in complex terrain (e.g., in urban, forested, and littoral areas);
- Multimission AV operations (e.g., changing mission objective or mission type);
- Autonomous collaboration of AVs with other manned and unmanned vehicles;
- Autonomous operations of AVs with noncollaborating vehicles in shared space;
- Autonomous target acquisition and engagement by AVs; and
- Tight integration of AVs with command-and-control systems (e.g., a vertically integrated command-and-control, mission management, and vehicle management software structure).

Most of the technologies required for full autonomy in these operational capabilities are not yet fully mature, and many are still reasonably far in the future. The following subsection describes some of the promising autonomy technologies under development today throughout the DOD to enable these key operational capabilities. The subsection entitled "Key Shortfalls in Autonomy Capability" then addresses the matter of where more intensive technology development may be warranted, given the relative value in achieving the overall vision.

Promising Technologies for the Future

Over the past 30 years, many DOD programs have developed and matured autonomy technologies too numerous to discuss in detail in this report. More recently, ONR's Autonomous Operations FNC initiated a four-pronged autonomy technology effort.[8] It includes the development of autonomy technology to be transitioned to the fleet for UAVs, UUVs, and UGVs, as well as the development of general-purpose autonomy technology under the Intelligent Autonomy Program. The UAV, UUV, and UGV domain efforts are primarily focused on vehicles, sensors, and sensor data processing technologies, with emphasis on transitioning those that are mature. It is important to emphasize sensor interpretation technology for scene interpretation (local terrain and other environment modeling) and for threat detection and identification, because as more autonomous functions are used for mission planning and collaborative control, the more automatic the sensor interpretation must be. The Intelligent Autonomy Program is focused on developing general-purpose autonomy technology for air, land, and

[8]For additional information, see the Web site <http://www.onr.navy.mil/fncs/auto_ops/>. Last accessed on May 18, 2004.

undersea systems. Many of these technologies have matured to the extent that they can enable new capabilities in Naval Services autonomous vehicles. The sampling of six technologies listed here, which are believed to have applicability in multiple autonomous vehicle domains (e.g., air, land, surface, and undersea), are discussed in the subsections below:

- Dynamic real-time mission planning and replanning,
- Simultaneous localization and mapping (SLAM),
- Threat detection and identification,
- Analytical redundancy and failure-detection filtering,
- Supervised learning and adaptation/learning technology, and
- Human-machine collaborative decision making.

Dynamic Real-Time Mission Planning and Replanning

The improvement of mission effectiveness, vehicle survivability, and system affordability for Naval Services autonomous vehicles will result in an increase in the number of functional mission capabilities (increased mission complexity) to be implemented in an AV and an increase in the degree of autonomy implemented in each. This increase in level of mission autonomy, coupled with an increase in environmental complexity (e.g., in threat-dense environments), drives the need for more agile and dynamic mission planning if operational tempo is not to be compromised. Dynamic mission-planning capabilities will be needed to autonomously generate time lines for mission activities, to handle failures and their possible impacts on other activities, to accommodate uncertainty in the description of the threats, to manage resources and consumables, and to plan mission activities collaboratively with other vehicles. Several new technologies are becoming available to help deal with this increasing mission complexity as described below. Moving this dynamic mission-planning capability onboard AVs will also reduce overall system complexity.

Conventional premission batch planning systems (e.g., the Tactical Aircraft Mission Planning System, Portable Flight Planning System, and Air Force Mission Support System) have the downside of slow operational tempo—that is, slow planning cycles with heavy human involvement to dynamically accommodate uncertainty or unanticipated events in complex systems. More recently, software frameworks for real-time planning systems have been developed to manage the complexity associated with a hierarchy of mission activities autonomously and dynamically, removing the burden from the human operators and mission planners. These software frameworks provide an application programming interface for dynamic, closed-loop planning of mission activities to generate activity time lines subject to constraints, accommodate perturbations in the plan owing to model uncertainties, manage failures and their impacts on other activities, negotiate resources with subordinate activities, and plan operations for aborting missions or removing vehicles to safety. These frameworks are then populated by planning, monitoring, and problem-diagnosis algorithms for each specific mission activity. Integration of these new software frameworks with conventional mission-planning systems will enable increases in operational tempo while reducing the burden on and size of the mission-planning and operations workforce.

The specific planning algorithms used within the software framework depend on the planning problem to be solved. Planning problems are traditionally optimization or classic branch and bound search problems. More recently, techniques have been developed for recasting planning problems as constraint satisfaction problems (CSPs) or for using composite variables to transform the optimization problem into a mathematical description of the operator's intent. A family of extremely fast CSP solution algorithms has been developed that, when carefully handcrafted, can provide solution times for even relatively complex planning problems within reactive time frames.[9]

Hierarchical task net planning is another important planning technology, which develops the plan through hierarchical refinement. At each level of the process, a plan capable of achieving the goal is retrieved from a library of existing plans. This plan is only partially refined—some of the substeps are primitive operators, but others are merely represented as subgoals to be achieved by further planning. Hybrid approaches are also possible: in particular, it is possible for a human to develop or select the higher levels of a plan while relying on computational techniques to transform the remaining subgoals into fully elaborated plans either at planning or execution time. "Reactive programming languages" have been developed as a means to express such higher-level plans.

More recently, robust hybrid automatons have been developed that make use of an algorithm that permits real-time generation of complex paths from a basic set of offline-generated agile maneuvers. The complex path is then generated online using an optimal solver that pieces together the required path, subject to a set of path constraints. This technique is used for obstacle avoidance when extremely fast reaction times are required of the system; it is especially useful for AV operations in complex environments.

[9]A. López-Ortiz, C. Quimper, J. Tromp, and P. van Beek. 2003. "A Fast and Simple Algorithm for Bounds Consistency of the Alldifferent Constraint," Paper #310, presented at the 18th International Joint Conference on Artificial Intelligence, Acapulco, Mexico, August.

Simultaneous Localization and Mapping

Navigation in GPS-denied environments has received considerable attention in recent years in order to improve the navigation of UGVs in most operating environments, that of UAVs in urban environments or under tree canopy, and that of UUVs in littoral waters (in Chapter 5, see the section entitled "Naval Operational Needs and Technology Issues," for UUVs). Sophisticated processing means are becoming popular for combining the functions of navigation and mapping to improve the quality of both. SLAM is a technique by which terrain objects or topography are entered into a map at the same time that the position and orientation of the vehicle is being estimated in those same map coordinates. A crucial effect of this technique is that when a piece of terrain (e.g., a feature or object) is seen again after the vehicle has moved significantly, the system performs a correlation between the old observations and the new, giving simultaneously a tremendous improvement in the map accuracy and in the vehicle navigation state. Such techniques can give highly accurate estimates of vehicle position and terrain topography. Furthermore, cooperative execution of such algorithms by multiple vehicles sharing a common data structure can quickly produce high-quality maps and localizations for all of the vehicles. This technique has been applied in relatively structured environments (e.g., inside buildings or tunnels), where features are noncomplex and easily recognized, using LIDAR, sonar, and vision sensor systems. This technology is less mature for operations in unstructured environments where features or map objects are of various shapes and sizes.

Most of the SLAM work to date has used commercial off-the-self sensors and focused on algorithm and software development. But in most cases the sensors involved are not in a form suitable for fielding. Thus, there is a significant gap in sensor development, particularly for intelligent autonomy for small UGVs. The Army Research Laboratory's Collaborative Technology Alliances Program is funding sensors germane to vehicles the size of the FCS Multifunction Utility Logistics Equipment (MULE) vehicle or larger.[10]

Threat Detection and Identification

As autonomous vehicles become more accepted, they will be called on to operate in more threat-dense environments. Real-time capability for threat detection and identification will be required for AV operations in these environments. Today, manned aircraft, surface ships, and submarines make use of threat radars, electro-optical (EO) and infrared (IR) sensing, and COMINT signal processing to detect and identify adversary threats and threat types. Many of these technologies

[10]For additional information, see the Web site <http://www.arl.army.mil/alliances/Default.htm>. Last accessed on May 18, 2004.

are transferable to AVs to enable operations in threat-dense environments. In order to operate on an AV, these systems will need to be augmented by planners for threat-response tactics that take the place of the pilots or operators to implement one of various strategies in response to a threat. Also, in many cases the sensors used on large, manned vehicles will be too big for AVs, or the ability for autonomous threat detection with high probability of detection and low false alarm rate is not very mature. Thus, more work is needed in this area.

Analytical Redundancy and Failure-Detection Filtering

Conventional approaches to monitoring and diagnosis of vehicle systems include the use of hardware redundancy for failure detection and isolation using input-output voting schemes, midvalue selection, and built-in testing. These methods by their nature can substantially increase the weight of the Vehicle Management System and do not by themselves help determine the lost functionality within a subsystem or the mode of the system owing to the failure. The latter is critical for a dynamic planning system to be able to determine the right course of action following a failure.

Analytical redundancy, which makes use of mathematical models of hardware subsystems to provide estimates of the expected sensor measurements or vehicle responses, does not require redundant hardware and can be used to determine the lost functionality within the affected subsystem. Analytical redundancy provides estimates of the expected sensor measurements or vehicle responses through estimation of theoretical approaches developed beginning in the 1940s and 1950s (e.g., the Wiener filter and the Kalman-Bucy filter).

Failure detection and isolation using analytical redundancy employ estimation of theoretical technologies such as hypothesis testing, maximum-likelihood detection, generalized likelihood ratio tests, and robust estimation, to detect and isolate system failures. These methods use linear filters to generate residuals between a model of the system and the measurements being received from onboard sensors. A failure in the dynamic system can be detected as a change in one or more of the plant parameters, or input signals. These faults can correspond to failed actuators or sensors or to failures that cannot be assigned to any system components (e.g., a UUV getting caught in a net).

In detection filter design, the filter gain is chosen so that the residual vector has a different fixed direction for each hypothesized component failure. Hypothesis tests describe the expected response of the system to the no-failure case and to selected candidate failures. Ratios of probabilities of the various failures to the no-failure response are computed and compared to a threshold to detect and isolate failures. The generalized likelihood ratio test is a statistical test that looks for a change in the statistical properties of the filter to declare a failure of a specific type. Robust estimation approaches modify the filter gains to accommodate uncertainties in the mathematical description of the subsystem processes being used.

These methods have been developed and tested for UUVs and are in use today in aircraft-engine health-monitoring systems, commercial-airline diagnostics and prognostication systems, and the guidance, navigation, and control systems of spacecraft and military aircraft.

Supervised Learning and Adaptation/Learning Technology

Learning and adaptation technologies have applicability for autonomous vehicle control, mission planning, failure diagnosis, sensing and perception, and collaboration. These technologies have matured over the past two decades to the point of being a useful component technology to improve mission effectiveness for specific mission activities or to improve vehicle survivability for specific critical-failure scenarios. However, this technology has not matured to the extent that it should be viewed as a panacea for the accommodation of unanticipated events for all mission activities.

There are three primary categories of learning and adaptation technology: (1) model approximation, (2) supervised learning and adaptation, and (3) reinforcement learning. The technologies within the first and second categories are mature enough today to be used on a limited basis for specific AV functions if the overall mission effectiveness and vehicle survivability will truly benefit from the expanded capability. Technologies within the third category are not mature enough to be used in AVs today.

Model approximation (category 1) makes use of connectionist (learning) networks of radial basis functions, sigmoidal functions, or Gaussian functions to represent complex physical processes that are otherwise difficult to model. Model-referenced adaptive control systems make use of this technology to expand the operating space for vehicle control systems and reduce modeling complexity. Learning-based model approximation has been used to model such things as the nonlinear flight dynamics of aircraft for flight control, aircraft jet-engine combustion for failure detection and isolation, helicopter gearbox models for failure detection, and chemical propagation for the detection and tracking of underwater plumes. Learning-based model approximation has also been used to generate models within planning systems, for state estimators, or for analytical failure detection and isolation. These techniques are heavily supported by simulation data to provide the initial network training, and subsequently they are supported by experiential data collected during the AV's operations.

The technique of supervised learning and adaptation uses a learning system in order to select the best (or a good) action to be implemented, given the current state of the system. The learning is said to be supervised since the selection of a good action uses a network trained through human supervision or simulation. The network is trained by computing a value function. The value function is a complex mapping that represents the benefit to be derived by the implementation of each possible action for all possible system states. It can be a mathematical function (e.g., a weighted combination of the system states and possibly previous actions) or the subjective opinion of "goodness," as determined by a human supervisor. The value function represents the benefit to be derived by implementation of all possible actions. Once the learning system has been trained via this supervision, the system has the ability to generate a good action given an arbitrary system state. Supervised learning systems have been applied to such things as AV controls, mission activity planning, and fault detection and isolation.

The technique of reinforcement learning and adaptation is the most difficult and by far the least mature at this stage of development. Reinforcement learning systems are systems capable of learning without access to an a priori provided value function. In this case, the system must learn the value function "on-the-fly," which requires that trial actions be explored for the inputs that currently exist, and then be quickly evaluated for "goodness." Many techniques have been developed for this purpose, including Q-Learning and neuro-dynamic programming, but each requires substantial computational resources or processing delays to implement the existing algorithms.

Human-Machine Collaborative Decision Making

Most autonomous vehicles for the foreseeable future will continue to operate under mixed-initiative control, in which decision making is shared by humans and automated systems. UUVs may be an exception to this rule, owing to the difficulty of communications in the underwater environment. For there to be a force-multiplier effect in the use of AVs, such decision making must involve a single human operator controlling several vehicles. Remote control of every vehicle by a single operator becomes impossible. This level of operator control (or conversely, level of autonomy) is a system design choice, as was previously pointed out. The desired level of human interaction to perform the functions described in Box 3.2 must be selected for each mission activity in the mission activity hierarchy for a particular system of AVs. As the number of vehicles to be controlled increases, so too does the required complexity of the human-machine interaction. The operator must know when to, and then be able to, take more control over mission activities at any time and for any level of the mission activity hierarchy, when required. Similarly, the automated systems must be better able to assess their ability to achieve the desired goals presented by the operator and then request help when needed. This variable or adjustable autonomy will likely be required to enable the Navy's vision of the future.

Technologies available to implement mixed-initiative control today are fairly limited and primarily point solutions to specific portions of the autonomous systems. For example, the planning and decision frameworks discussed in the section above entitled "Dynamic Real-Time Mission Planning and Replanning" provide a rudimentary (first) capability for the operator to interact with the system during any mission activity and at any level of the mission activity hierarchy. These interactions can be for the purpose of mission planning, plan execution monitoring, plan problem diagnosis, and authorization of planned activities. Although these frameworks do not preclude the use of variable levels of autonomy for mission activities, they do not presently support this capability either. Similarly, systems that are used to generate situation awareness (e.g., threat detection and response) typically implement a fixed, human-machine interaction protocol. Much work remains in order to develop a system architecture for autonomous systems and the methods that support mixed-initiative control with variable levels of autonomy for planning and decision, sensing and perception, and monitoring and diagnosis.

Key Shortfalls in Autonomy Capability

Despite the autonomy capabilities that can now be leveraged from the DOD's autonomy technology portfolio or that are currently being developed via ONR's Autonomous Operations FNC, much remains to be done if the Navy's future vision is to be fully realized. The focus of future Naval Services' investments and the pace of autonomy technology development must be carefully mapped, with cognizance of work being done across the DOD, including work by the Army, the Air Force, and the Defense Advanced Research Projects Agency (DARPA). Table 3.2 lists the top two or three general shortfalls in autonomy capability that need to be remedied in order to enable the operational capabilities described by the DOD's vision expressed in the 2001 Quadrennial Defense Review[11] and in the Navy's Sea Power 21.[12] These shortfalls represent areas in which more intensive, Navy- or Marine Corps-specific development focus may provide the greatest value in enabling new operational capabilities for the Naval Services. For each shortfall in capability, the table lists the level of technology development recommended by the committee, possible future programs (transition targets) that would benefit from the development, a description of the capability needed, and some items to be considered as part of the technology development. Implicit in the recommended level of technology development is the current level of technology maturity that could be built upon to create the new operational capability.

[11]Donald H. Rumsfeld, Secretary of Defense. 2001. *Quadrennial Defense Review Report,* U.S. Government Printing Office, Washington, D.C., September 30. Available online at <http://www.defenselink.mil/pubs/qdr2001.pdf>. Accessed on May 13, 2005.

[12]ADM Vern Clark, USN. 2002. "Sea Power 21: Projecting Decisive Joint Capabilities," *U.S. Naval Institute Proceedings*, Vol. 128, No. 10, pp. 32-41.

TABLE 3.2 Key Autonomy Capabilities Shortfalls, by Technology Area, with the Level of Technology Development Recommended by the Committee and Future Programs That Would Benefit

Technology Area	Shortfalls in Autonomy Capability	Recommended S&T Level[a]	Of Benefit to Possible Future Programs	Description of Needed Capability	Key Considerations
Planning and decision	Dynamic mission planning for teams	6.2/6.3	LCS UCAV Mine interdiction warfare systems	Develop a capability for dynamic planning of high-level mission activities involving small teams of vehicles (manned or unmanned). Includes planning for all phases, e.g., launch, ingress, operations, egress, and recovery.	Vertical integration of team mission planning with C2, including method of team control (e.g., through master vehicle in master-slave arrangement or through each member of team in peer-to-peer arrangement). How will integrated system deal with targeting?
	Threat-response tactics planning	6.1	UCAV	Develop a capability for real-time threat-response-tactics planning, which decides among options involving avoidance of threat, defense against threat with countermeasures, evasion of threat through maneuvering, or attack of threat with available weapons.	Explore benefit of dynamic concurrent threat-response planning (concurrent with nominal mission planning) versus using reactive preprogrammed tactics.
Sensing and perception	Human-machine collaborative threat and/or target identification and classification	6.3	UCAV Multi-reconfigurable unmanned undersea vehicle (MRUUV)	Integrate currently available algorithms with appropriate sensor modalities to demonstrate automatic target cueing capability. Operationalize existing, but immature, technology by adding human interface to allow human-machine collaboration.	Consider focusing on currently available EO, IR, SAR sensor technology.

	Human-machine collaborative exploitation of sensor information Sensor development for intelligent autonomy for small vehicles. Perception for autonomous navigation.	6.1/6.2	FORCEnet	Develop human-machine collaborative decision-making tools that have increased levels of autonomy for target-of-opportunity detection, classification and/or identification, exploitation in context, verification, and prioritization. Integrate these autonomy tools with system.	Consider the distribution of autonomy between autonomous vehicles collecting information, operator control stations, and intelligence exploitation centers.
Monitoring and diagnosis	Mission- and/or system-level problem detection, diagnosis, and reconfiguration	6.1/6.2	UCAV MRUUV	Develop a capability to use FMEA, with system component coverage and failure rates to detect and diagnose current and emerging problems in autonomous systems and then to assess the impact of the problem on mission plans. Includes systems of multiple vehicles and communication back to home base(s).	Consider multiple levels of autonomy through human-machine collaboration.
Networking and collaboration	Secure, assured networking for multivehicle collaboration	6.1/6.2	LCS UCAV Mine interdiction warfare systems	Develop a capability to autonomously manage the network of a small team of vehicles collaboratively planning and generating situation awareness.	Consider missions in which all vehicles are operating in open terrain and missions in which one or more vehicles are operating in complex environments (e.g., urban environments, underwater, under canopy).

continued

TABLE 3.2 Continued

Technology Area	Shortfalls in Autonomy Capability	Recommended S&T Level[a]	Of Benefit to Possible Future Programs	Description of Needed Capability	Key Considerations
Learning and adaptation	Real-time learning for adaptation to unanticipated events	6.1	UCAV MRUUV Submarine track and trail	Develop a capability to learn to adapt "on-the-fly" to unanticipated events. Includes events that were not anticipated but that *might* occur prior to the mission and for which the value function for several competing responses to the event needs to be learned quickly.	Solution may be application-specific. For example, problems of failure reconfiguration may require approaches different from those for problems involving learning and responding to adversary tactics.
Human-system interface	Natural user interfaces (e.g., natural language, gestures, symbology)	6.1	General	Develop the capability for an autonomous system to understand natural language or gestures of military operators or controllers.	Very difficult problem to be solved generally. Consider focusing on specific high-value Navy or Marine Corps needs such as UAV deck operations, manned-unmanned aircraft operations, UGV control via gestures or hand signals, or launch-and-recovery operations.
	Variable initiative control	6.2	UCAV MRUUV Other multimission capable AVs	Develop the capability for human operators to exert temporal variations of control over missions and activities during mission operations.	Multiple levels of autonomy depending on operator workload and vehicle and/or mission state.

[a]Science and technology (S&T) levels: 6.1, basic research; 6.2, applied research; 6.3, advanced technology development.
NOTE: A list of acronyms is provided in Appendix D.

CONCLUSIONS AND RECOMMENDATIONS

Autonomous Vehicle Concepts and Developments

As discussed above, the Office of Naval Research's Autonomous Operations Future Naval Capability has initiated a four-pronged autonomy technology development effort. This effort, in concert with the DOD's autonomy technology portfolio and ongoing DOD programs, provides a pipeline of maturing technologies that can be used to create, in the near term, new Navy and Marine Corps autonomous vehicle capabilities. Some examples include the following:

- For UAVs and UGVs, the adoption and adaptation of the dynamic real-time mission-planning technology used in UUVs and on spacecraft;
- The adoption of avionics architectures from spacecraft and manned systems to permit the migration of mission management autonomy software onboard autonomous vehicles;
- The adaptation of a dynamic real-time mission-level planning module, such as that developed under DARPA Mixed Initiative Control of Automa-Teams or the ongoing DARPA Jaguar Programs, with existing flight-planning systems such as the Navy's Portable Flight Planning System or the Joint Mission Planning System;
- The automation of existing manned aircraft threat-detection and -response capabilities for use in autonomous vehicles of all types;
- The adaptation of existing automatic target-recognition technology to operationalize semiautonomous versions of the technology using human collaboration; and
- The use of analytical redundancy and the built-in test and diagnostics capabilities in subsystem equipment to provide enhanced system reliability.

Autonomous Vehicle Technologies

The focus of future Naval Services investments and the pace of autonomy technology development need to be carefully mapped, with cognizance of work being done across the DOD, including that of the Army, Air Force, and DARPA. Table 3.2 lists some of the shortfalls in autonomy capability that need to be remedied in order to achieve the Navy's future vision—in these areas the committee believes that development focused on Navy-unique capabilities is required to raise the maturity of the technology to moderate levels. The committee believes that investments are needed in those technologies that improve the following:

- The ability for AVs to operate in threat-dense environments,
- The ability for human operators and/or intelligence analysts to collaborate with computers to interpret and exploit AV sensor data,

- The ability of AVs to network and collaborate with other autonomous and manned vehicles,
- The ability of AVs to detect and diagnose mission- and system-level problems and to reconfigure in order to accommodate them,
- The ability of AVs to perform multiple missions, and
- The ability of UAVs and UUVs to perform autonomous shipboard launch-and-recovery operations.

Incorporate Level of Mission Autonomy as Autonomous Vehicle Design Trade-off

System designers of autonomous vehicles often neglect the potential operational benefits to be derived by employing level of mission autonomy as a design choice in up-front trade-off studies, instead electing to focus on trade-offs relating to vehicle performance characteristics (e.g., speed, range, endurance, stealth) and subsystem capability (e.g., sensing and communications). This approach constrains the level of autonomy that can be implemented later in the development and prevents designs that might provide greater operational benefit in terms of impacting mission effectiveness, vehicle survivability, and system afford-ability. Early-stage AV design trade-offs can include the vertical integration of the AV system with its command-and-control system for the end-to-end operations to be performed by the system, including allocation and assignment, mission tasking (e.g., intelligence, surveillance, and reconnaissance; strike; logistics), collection, exploitation, and dissemination. Including the level of mission autonomy as a design choice enables several additional benefits to be derived, such as these:

- Prioritized, targeted technology development investments for Navy and Marine Corps autonomous vehicle needs based on determining those technologies that will have the greatest benefit;
- Reduced system complexity achieved through an increase in onboard mission autonomy;
- Improved autonomous vehicle mission effectiveness and survivability resulting from shorter planning and decision-making cycles; faster assimilation and interpretation of sensor information; faster detection, isolation, and assessment of system problems; shared mission objectives among collaborators; and expanded use of offboard sensor information; and
- Reduced total cost of autonomous vehicle ownership resulting from reduced operator support for planning, decision, and collaboration; reduced operator support for sensor interpretation and exploitation; reduced operator support for monitoring and problem diagnosis; reduced maintenance labor for trouble-shooting and prognostication; higher system reliability and reduced probability

of loss of vehicle; and shared use of distributed resources (e.g., sensors, weapons, and so on).

Autonomous Technology Recommendations

Recommendation: The Assistant Secretary of the Navy for Research, Development, and Acquisition (ASN(RD&A)) and the Chief of Naval Research (CNR) should direct the Navy and Marine Corps Systems Commands, the Office of Naval Research (ONR), and the Marine Corps Warfighting Laboratory (MCWL) to partner with the operational community and monitor the concepts and development of critical autonomous vehicle-related technologies considered essential to the accomplishment of future naval missions. The progress of these developments should be tracked year to year. Specifically:

Pursue New Autonomy Concepts and Technology Developments. The ASN (RD&A) should direct appropriate agencies in the Navy and Marine Corps to formulate and maintain a list of the most promising moderately to highly mature autonomy technologies (Technology Readiness Level: TRL > 4) that can enable, critical near-term autonomous vehicle capabilities. Plans to pursue further development of these capabilities should be developed and funded, and progress should be tracked year to year to ensure the proper pace of development.

The ONR should develop autonomous vehicle research and development (R&D) needs and a technology roadmap to achieve the goals defined by the various vision documents of the Naval Services. ONR should leverage the current operational experience and the recommended increase in future operational experience with autonomous vehicles in order to define R&D needs to address specific, high-value operational needs.

Recommendation: The Assistant Secretary of the Navy for Research, Development, and Acquisition (ASN(RD&A)) should mandate that level of mission autonomy be included as a required up-front design trade-off in all unmanned vehicle system development contracts. Specifically:

Incorporate Level of Mission Autonomy as an Autonomous Vehicle Design Trade-off. The ASN(RD&A) should direct appropriate agencies in the Navy and Marine Corps to exploit level of mission autonomy as a degree of freedom for impacting concepts of operations, mission effectiveness, vehicle survivability, and system affordability by including a level of mission autonomy as a design choice in the early-stage system trade-off studies. The architecture of all new autonomous vehicles should be such that increasing levels of autonomy can be implemented in the field by modular replacement and/or software upgrade.

4

Unmanned Aerial Vehicles: Capabilities and Potential

INTRODUCTION

The recent wars in Afghanistan and Iraq have shown that improved acquisition and rapid dissemination of intelligence, surveillance, and reconnaissance (ISR) information were important contributors to success in these campaigns. More specifically, it is well recognized that these campaigns benefited significantly from the ISR contributions of unmanned aerial vehicles (UAVs).

As with the evolution of most new military concepts, the path to acceptance of UAVs and recognition of their worth has been protracted and strewn with obstacles. The use of unmanned aircraft, as target vehicles and air-to-surface weapons, dates back to World War II. Camera-equipped Ryan Firebee drones enjoyed great success during the Vietnam War, flying some 3,400 sorties over heavily defended North Vietnam; among these were a few missions launched from aircraft carriers. But despite the promise of early experiments and operational deployments, the U.S. military has until recently been slow to invest in UAV development and reluctant to incorporate unmanned systems into the regular force structure. Looking back, it appears that earlier introduction of UAVs was impeded by several factors—such as immature technologies and a general lack of recognition by advocates that unmanned systems demand aerospace-quality treatment in design and manufacture.

Over the past several years however, a confluence of recognized needs and technological advances has brought about a marked change in the perceived military value of UAVs. These needs and advances include the following:

- The emergence of the requirement for continuous, or "persistent," surveillance;

- A strong desire to minimize casualties to or capture of aircrews;
- Dramatic increases in computer processing power and associated software advances;
- Advanced sensor technologies that make possible high resolution with much-reduced sensor size and weight;
- Improved communications, image-processing, and image-exploitation capabilities;
- Increased recognition by UAV advocates in industry and government that aerospace-quality expertise is essential because a model-airplane, "hobby-shop" approach to development will not yield reliable and militarily useful unmanned air systems;
- Advances in the efficiencies and reductions in size and weight of propulsion systems; and
- The availability of robust, long-endurance UAV platforms resulting from visionary investments by the Defense Advanced Research Projects Agency (DARPA).

In addition, and perhaps most importantly, the generally high marks accorded to UAVs—to the Predator (Figure 4.1) and the Hunter in the 1999 air war against Serbia, the Predator and Global Hawk (Figure 4.2) during Afghanistan operations, and UAVs in general in Operation Iraqi Freedom—have dramatically altered perceptions of the overall importance of UAVs in combat.

In response to emerging operational needs, the Air Force has committed to increased production rates for the Predator and Global Hawk, the Army is fielding its Shadow 200 tactical system (Figure 4.3) in increasing numbers, and the Army has selected the Fire Scout (Figure 4.4) as a key element of its Future Combat System (FCS). For its part, the Navy has committed to acquire a few Global Hawks for experimentation and has plans to make both high-altitude, long-endurance (HALE) and ship-based tactical ISR UAV systems operational by the end of this decade. In addition, DARPA, the Air Force Office of Scientific Research (AFOSR), and the Office of Naval Research (ONR) are pursuing a number of UAV Advanced Technology Demonstrations (ATDs) in concert with the military Services—these involve fighter-like air vehicles for lethal missions (the Joint Unmanned Combat Air System (J-UCAS)[1]) (Figure 4.5), rotorcraft for attack and long-endurance ISR

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[1]The J-UCAS program combines the efforts that were previously known as the DARPA/U.S. Air Force (USAF) Uninhabited Combat Air Vehicle (UCAV) and the DARPA/U.S. Navy (USN) Naval Uninhabited Combat Air Vehicle (UCAV-N) programs. The J-UCAS program is a joint DARPA/Air Force/Navy effort to demonstrate the technical feasibility, military utility, and operational value for weaponized unmanned aerial vehicles to prosecute 21st-century combat missions, including suppression of enemy air defense, surveillance, and precision strike. Additional information is available at the Web site <http://www.darpa.mil/j-ucas/>. Last accessed on April 5, 2004.

MQ-1 Predator/General Atomics/Air Force

Weight:	2250 lb
Length:	28.7 ft
Wingspan:	48.7 ft
Payload:	450 lb
Ceiling:	25,000 ft
Radius:	400 nm
Endurance:	24+ hr

FIGURE 4.1 MQ-1 Predator. SOURCE: Office of the Secretary of Defense. 2002. *Unmanned Aerial Vehicles Roadmap 2002-2027,* Department of Defense, Washington, D.C., December, p. 6.

RQ-4 Global Hawk/Northrop Grumman/Air Force

Weight:	26,750 lb
Length:	44.4 ft
Wingspan:	116.2 ft
Payload:	1950 lb
Ceiling:	65,000 ft
Radius:	5400 nm
Endurance:	32 hr

FIGURE 4.2 RQ-4 Global Hawk. SOURCE: Office of the Secretary of Defense. 2002. *Unmanned Aerial Vehicles Roadmap 2002-2027,* Department of Defense, Washington, D.C., December, p. 8.

RQ-7 Shadow 200/AAI/Army

Weight:	327 lb
Length:	11.2 ft
Wingspan:	12.8 ft
Payload:	60 lb
Ceiling:	15,000 ft
Radius:	68 nm
Endurance:	4 hr

FIGURE 4.3 RQ-7 Shadow. SOURCE: Office of the Secretary of Defense. 2002. *Unmanned Aerial Vehicles Roadmap 2002-2027,* Department of Defense, Washington, D.C., December, p. 8.

RQ-8 Fire Scout/Northrop Grumman/Navy

Weight:	2650 lb
Length:	22.9 ft
Rotorspan:	27.5 ft
Payload:	300 lb
Ceiling:	19,000 ft
Radius:	150 nm
Endurance:	5+ hr

FIGURE 4.4 RQ-8 Fire Scout. SOURCE: Office of the Secretary of Defense. 2002. *Unmanned Aerial Vehicles Roadmap 2002-2027,* Department of Defense, Washington, D.C., December, p. 9.

UCAV-N/DARPA Navy

Weight:	29,000 lb
Length:	34 ft
Wingspan:	50 ft
Payload:	5,500 lb
Ceiling:	40,000 ft
Radius:	1,500 nm
Endurance:	12 hr

FIGURE 4.5 UCAV-N. SOURCE: Office of the Secretary of Defense. 2002. *Unmanned Aerial Vehicles Roadmap 2002-2027,* Department of Defense, Washington, D.C., p. 12.

A160 Hummingbird/Frontier/DARPA

Weight:	4000 lb
Length:	35 ft
Rotorspan:	36 ft
Payload:	300+ lb
Ceiling:	30,000 ft
Radius:	1500 nm
Endurance:	24+ hr

FIGURE 4.6 A-160 Hummingbird. SOURCE: Office of the Secretary of Defense. 2002. *Unmanned Aerial Vehicles Roadmap 2002-2027,* Department of Defense, Washington, D.C., December, p. 18.

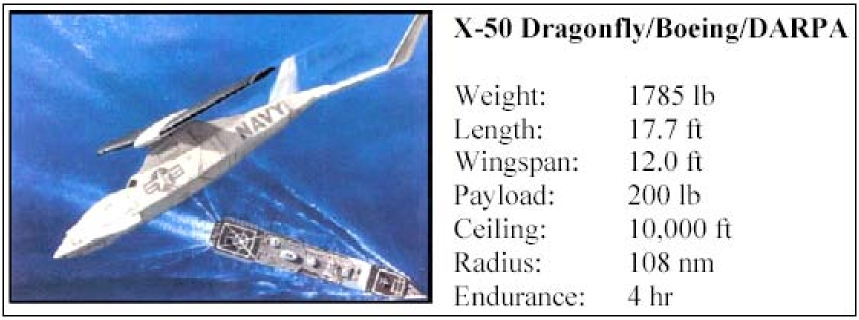
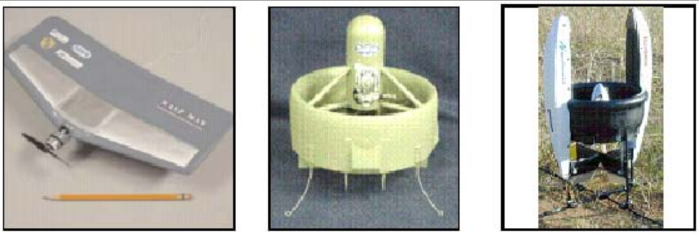


FIGURE 4.7 X-50 Dragonfly. SOURCE: Office of the Secretary of Defense. 2002. *Unmanned Aerial Vehicles Roadmap 2002-2027,* Department of Defense, Washington, D.C., December, p. 18.

FIGURE 4.8 UCAR. SOURCE: Office of the Secretary of Defense. 2002. *Unmanned Aerial Vehicles Roadmap 2002-2027,* Department of Defense, Washington, D.C., December, p. 13.



	Wasp AeroVironment	iStar Allied Aerospace	Kestrel Honeywell
Weight:	.04 lb	5 lb	25 lb
Length:	8 in	12 in	42 in
Diameter:	13 in wingspan	9 in	17 in
Payload:	.01 lb	1 lb	10 lb
Ceiling:	1200 ft	16,000 ft	TBD
Radius:	0.5 nm	5.5 nm	11 nm
Endurance:	100 min	40 min	120 min

FIGURE 4.9 Micro UAVs. SOURCE: Office of the Secretary of Defense. 2002. *Unmanned Aerial Vehicles Roadmap 2002-2027,* Department of Defense, Washington, D.C., December, p. 19.

(the A-160 Hummingbird) (Figure 4.6), the X-50 Dragonfly canard rotor wing (CRW) (Figure 4.7), unmanned combat armed rotorcraft (UCAR) (Figure 4.8), and small or micro-UAVs (Figure 4.9) for urban combat.

The remainder of this chapter discusses the naval UAV operational missions, the potential of UAVs for naval operations, related technology issues and needs, and the findings and recommendations of the committee. The UAV systems directly related to the recommendations of this study fall into three operational categories: (1) intelligence, surveillance, and reconnaissance; (2) strike (i.e., uninhabited combat air vehicles (UCAVs)); and (3) combat support. UAVs not related to the recommendations but still of current or potential interest for naval operations are described in Appendix C, in the section entitled "Other Unmanned Aerial Vehicle Programs." Readers interested in broader and more detailed coverage are referred to the current Department of Defense (DOD) UAV Roadmap.[2]

[2]Office of the Secretary of Defense. 2002. *Unmanned Aerial Vehicles Roadmap 2002-2027,* Department of Defense, Washington, D.C., December.

OPERATIONAL CATEGORIES OF NAVAL UNMANNED AERIAL VEHICLE MISSIONS

The introduction of UAVs into the battlespace enables impressive new operational capabilities for naval forces across the operational mission spectrum. These capabilities can be categorized in the three broad mission-area types enumerated above: (1) ISR, (2) strike, and (3) combat support. The categories are discussed in the following subsections.

Intelligence, Surveillance, and Reconnaissance

"ISR" is the term commonly used to characterize operational missions that employ sensors rather than weapons. This broad operational category is often further subdivided, depending on the intended use of the data gathered by the mission—for example, theater ISR, tactical ISR, and human-portable or small-unit ISR. Some of the unique challenges associated with ISR UAV operations in support of naval operations are elaborated on in the next major section.

Strike

In its broad sense, "strike" refers to operational missions that put weapons rather than sensors on target. This category is further subdivided as follows:

- Strike, consisting of all types of air-to-ground missions intended to put weapons on target, but not in close proximity to ground combatants;
- Suppression/destruction of enemy air defense (SEAD/DEAD), preemptive or reactive; and
- Close air support (CAS), consisting of air-to-ground strikes in support of and in close proximity to troops in combat.

The current UAV focus in the strike mission area is on the use of armed UCAVs, primarily for SEAD and DEAD. In addition, UCAVs can make a large number of potentially significant contributions, from straightforward extensions of manned aircraft strike missions (e.g., fixed-target strikes) to missions based on completely new concepts (e.g., forward-pass CAS missions that are directly controlled by ground-based forward observers or forward air controllers). These concepts are discussed later in the chapter, and in the subsection entitled "Recommendations Concerning Unmanned Aerial Vehicles," the committee addresses Navy and Marine Corps efforts to explore and experiment with some of these new technologies and concepts of operations (CONOPS).

Many targets in a deep-strike mission may be well defended. In the future, given the availability of high-technology weapons systems and network technology on the open market, it is likely that the integrated air defenses of U.S.

adversaries will be very capable. UAVs will need low signatures to survive, but stealth alone is unlikely to protect an air vehicle that loiters for a significant period of time in view of networked air defenses. To protect UAVs on such missions, the UAVs may have to be employed in numbers and individually pass in and out of view of air defenses, or they themselves may need to be capable of attacking opposing defenses. Furthermore, UAVs may have to employ self-defense measures normally employed on manned aircraft, such as deploying decoys, launching antiradiation weapons to attack enemy air defense radars, or engaging incoming surface-to-air missiles with air-to-air weapons. The next major section discusses how the suppression of enemy air defense through electronic warfare can also improve the survivability of air platforms.

Combat Support

"Combat support" encompasses operational missions that support combat operations, including jamming and other forms of electronic attack, communications relay, logistics resupply, and decoy. The current UAV focus in this mission area is on the use of HALE and tactical UAVs (TUAVs) for communications relay. Some consideration has also been given to using UAVs and UCAVs for jamming and electronic attack. Combat support is another mission area that will benefit from innovative exploration and experimentation with UAVs, as discussed further in following sections.

THE POTENTIAL OF UNMANNED AERIAL VEHICLES FOR NAVAL OPERATIONS

Unmanned aerial vehicles capitalize on many of the advantages that have made manned aircraft so vital to military operations. They operate in a medium that allows easy movement in three dimensions and which is penetrable by a broad variety of sensing and communications techniques. Operation at altitude provides direct lines of sight for sensors and facilitates weapons delivery. The characteristics of the atmosphere and the range of UAV operating altitudes allow direct communication with other aircraft, satellites, and other elements located over large areas of Earth's surface. Their global reach and speed of movement, relative to surface modes, allow UAVs to serve as sensor and weapons platforms, extending awareness and influence in a timely fashion over broad areas.

Also, as a result of the enormous investments previously made in manned aircraft, UAV developments have many highly mature technology bases to draw from, including those of aerodynamics, propulsion, structures, materials, systems, maintenance, logistics, and operations. Although there are unique technical challenges associated with UAVs, the great majority of experience gained over decades of manned aircraft development applies to UAVs.

Furthermore, UAVs avoid many of the difficulties that are inherent in manned aircraft. Those difficulties include, for example, operational and physical issues associated with manned aircraft operations above altitudes of approximately 50,000 ft, which are orders of magnitude more complex than for operations at lower altitudes. Pressure suits are required for the crew, crew acclimatization is required pre- and postmission, and limitations are placed on individual flight rates. In particular, Air Force U-2 pilots who fly high-altitude missions for more than 12 hours are typically grounded for 24 to 48 hours before they can fly their next mission. Other advantages accruing to UAVs because of being unmanned include the lack of weight, size, orientation, maneuver or environmental penalties, or restrictions that would otherwise be imposed by crew requirements.

In addition UAVs (singly and in combination) enable new capabilities that translate into significant operational benefits for naval forces. Listed below are those that the committee considers to be the most compelling. They are grouped in three broad capability categories: (1) increased operational flexibility, (2) new operational capabilities, and (3) reduced cost, as discussed in the following subsections.

Increased Operational Flexibility

Persistent Air Operations

UAVs can stay on station in or near the combat area far beyond the capabilities of manned systems. Although there are practical and theoretical limits (see Appendix B), by employing a small number of vehicles, these impressive capabilities enable near-continuous surveillance for essentially indefinite periods of time. As demonstrated in Afghanistan and Iraq, the operational flexibility is further enhanced when both ISR and strike are integrated into one air vehicle such as the Predator.

Deck-Cycle Flexibility

The benefits of long endurance translate into more than the amount of time on station over the combat area. A long-endurance capability can also allow naval air assets to fly minimum-impact defensive missions during periods when carriers are otherwise not conducting regular air operations. In this context, minimum impact means that the assets can be kept airborne with minimum impact on deck crew and support personnel readiness.

Time Line Flexibility

Long-endurance platform capabilities can also be used to give naval forces an ability to execute complex ISR and strike operations many hours into a flight that would otherwise strain the capabilities of traditional aircrews. For example, a set of armed strike UCAVs could stay on combat air patrol continuously, ready to execute a complex, precisely timed multivehicle strike. In addition, technology is now available that would allow these kinds of missions to be replanned and initiated within seconds. Such technologies were developed by DARPA's Joint Forces Air Component Commander (JFACC) Program and its subsequently established Mixed Initiative Control of Automa-teams (MICA) Program.

Reach-Back and Other Forms of Virtual Support

Recent events have clearly demonstrated the significant operational benefit of forward-deploying theater-level UAVs while physically locating mission-control and data-exploitation elements elsewhere. This arrangement allows some key functions such as ISR product analysis and exploitation to be performed remotely, thereby reducing deployment requirements and allowing tasks to be performed by civilian specialists outside the combat zone.

Distributed Control

Although both manned and unmanned air operations can be coordinated among multiple users, the physical removal of the operator from the air vehicle also allows direct control to be shared among multiple users or even Services. The user with the best situation awareness or the most immediate need could assume direct control as needed. For example, a SEAL (sea, air, land) team could (1) transmit target coordinates by data link to a UCAV flying in support of its mission, (2) quickly confirm receipt of correct target coordinates, (3) command weapon release, and (4) hand off the UCAV to another user. This concept of direct control by local users has the potential to substantially reduce the time lines for air-to-ground coordination and target prosecution.[3]

New Concept of "Joint"

The concept of virtual support of naval forces could logically include taking operational control (versus tasking) of UAVs operated by other DOD organizations and government agencies. For example, the Air Force currently operates the land-based Predator and Global Hawk high-altitude, long-endurance ISR systems. The Navy's Broad Area Maritime Surveillance (BAMS) initiative envi-

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[3]Armand J. Chaput, Ken C. Henson, and Robert A. Ruszkowski, Jr. 1999. "UCAV Concepts for CAS," paper presented at the North Atlantic Treaty Organization Research and Technology Organization Symposium on Advances in Vehicle Systems Concepts and Integration, Ankara, Turkey, April.

sions the use of a similar land-based system to meet next-generation, organic naval forces ISR requirements. Conceivably, one system type (with some sensor development) could meet both requirements. Although this would increase current levels of inter-Service dependence, the committee sees no reason why a single fleet of HALE UAVs would not be able to serve both Services' land-based UAV ISR requirements.

New Operational Capabilities

The Navy and Marine Corps need to consider innovative concepts in order to exploit the potential that UAVs offer. This endeavor will involve pursuing advanced development in concept areas such as those discussed below and leveraging the efforts of other military Services, DARPA, and other innovative institutions.

Operations in Dirty Environments

Even though returning a UAV from a contaminated environment will challenge ship- and land-based operations and support personnel, UAVs and UCAVs still have an advantage in that they can be more tightly sealed and do not have to be opened up to change out the crew and decontaminate the cockpit.

Aerial Refueling for Selected Future UAV Systems

Aircraft that use consumable fuel are inherently limited in their endurance on station because of the finite quantity of fuel that they can carry. A well-developed approach to avoid this fundamental limitation and extend the endurance of consumable-fuel aircraft is that of aerial refueling. Aerial refueling is a common practice with manned aircraft; it allows the long-distance ferry flight of aircraft with inherently limited range and increases their endurance on station. Predator-class and smaller UAVs fly too slowly to refuel with either the Air Force or Navy refueling infrastructure. The only refueling infrastructure currently applicable is the C-130 used for refueling helicopters. Through its Automated Aerial Refueling Program, the Air Force Research Laboratory (AFRL) is evaluating aerial refueling as part of its UCAV program. This effort will address many of the fundamental issues associated with autonomous or teleoperated refueling. However, the Air Force approach to refueling uses an operator-controlled boom, differing from the Navy approach of a "probe and drogue" in which the pilot of the receiving aircraft controls the approach and connection to the tanker aircraft. Concepts now exist for stabilizing or actively controlling the position of the drogue relative to the probe. Aerial refueling is part of the Joint Unmanned Combat Air System (J-UCAS). The Navy could foster the development of technologies suitable for UAV aerial refueling—UAVs could operate both as a tanker and as a receiver aircraft.

J-UCAS as Combat Air Patrol and Airborne Early Warning Platform

The primary airborne early warning (AEW) of low-flying aircraft or antiship missiles and radar surveillance for combat air patrol (CAP) are provided by ship-based radar and airborne surveillance aircraft such as the E-2C. The use of radar surveillance exacerbates the patrol aircraft's vulnerability to enemy fire because the radar transmitter signal gives away its presence and current location and can be exploited by a radio-frequency homing missile. This vulnerability can be eliminated by using a bistatic arrangement in which only the radar receiver is on the patrol aircraft. The radar transmitter is kept out of harm's way in a safe, rearward "sanctuary" location. The penalty for this arrangement is an increased Reynolds number loss on the transmitter leg of the radar signal path. However, because the airborne platform is thus made more "stealthy," some of this loss can be compensated for by moving the platform closer to the surveillance area and so reducing the Reynolds number loss on the receiver leg.

UAVs could play a natural role in this arrangement by carrying the receiver antenna and being placed forward, closer to likely axes of threat approach, with the manned aircraft transmitting from a position closer to the fleet or away from the combat area. This arrangement would maintain the performance of the radar system while keeping the manned aircraft farther from hazardous areas.

An alternate UCAV CAP approach would use long-endurance, low-signature UCAVs to loiter far forward, ready to respond to approaching air threats. Such a CAP UCAV could be directed by ship- or other aircraft-based sensors or by its own sensors, and it could provide rapid reaction to threats at some distance from the ships or facilities being protected.

J-UCAS as Close Air Support Platform

As demonstrated in recent operations in Iraq and Afghanistan, armed loitering Predator UAVs are excellent platforms for providing precisely delivered air support for ground operations. Another effective platform for supporting ground operations was a loitering B-52 with independently targetable Global Positioning System (GPS)-guided weapons. A logical extension of these lessons learned would be to employ a J-UCAS as a stealthy, forward-deployed, loitering platform in support of ground operations, but under the direct control of the Marine Corps forward air controllers. In this concept, the forward observers would provide target coordinates by data link directly to the UCAV fire-control computer, which would respond with the coordinates as received. Upon confirmation that the weapon was correctly targeted, the forward air controller could authorize the weapon release. This form of direct Marine-to-machine interface would significantly reduce the time normally required to coordinate an air-to-ground CAS strike as well as reducing the potential for friendly-fire incidents.

Very Small UAV Systems

DARPA is currently sponsoring exploratory development in micro-UAVs, with characteristic dimensions of 6 in. These UAVs are intended to be easily transported by an individual soldier or Marine (for example, in a fatigue shirt pocket). The mission of such UAVs would be to extend the value of organic air vehicles to the individual. In the future, even smaller UAVs might be possible, perhaps extending into the regime of medium-sized flying insects. These smaller UAVs would extend the "eyes" of the soldier into confined spaces while avoiding surface obstacles that would impede the movement of ground vehicles. Such small UAVs could find application in urban environments and in tunnels and caves. One application of small, disposable UAVs is that of being piggybacked with a weapon in order to do bomb damage assessment right after bombing. Continued research to understand the low Reynolds number physics of these mini- and microvehicles is warranted, in particular on those with complex, biomimetic components.

UAVs That Deploy Unattended Ground Sensors or Smaller Sensor and Attack Systems

UAVs as currently envisioned and realized would often be deployed in a combat arena and equipped with remote sensors to acquire ISR data. However, in some cases there may be information that can only be acquired or is best acquired by in situ sensors. Examples include the sensing of chemical or biological agents in advance of moving ground forces into an area, or the emplacement of unattended ground sensors for long-duration monitoring of an area of interest. In other cases, there may be a favorable trade-off between the smaller size of sensor aperture and less power required by a smaller platform placed closer to the ground than would be prudent with a larger UAV. Some relevant work has been done on enabling technologies, including, for example, the Predator, which has carried and released the Finder, a small UAV. There has been extensive work on air-dropped, unattended ground sensors, and some work has been done on miniature, GPS-guided, payload delivery systems.

Aerial Release and Redocking for Offboard Sensor Platforms and Other Applications

An extension of using UAVs to deploy unattended ground sensors or smaller sensor and attack systems would be to allow the redocking of a smaller air vehicle to the carrier aircraft (either manned or unmanned). This process would allow the retrieval of sensors, samples, or other high-value systems. Although there are undoubtedly many approaches to aerial release and redocking, one possible technique could combine a capability for autonomous probe-and-drogue aerial refueling, as discussed earlier, with the current techniques for deploying and retrieving towed aerial gunnery targets.

Extreme-Endurance Systems

As discussed earlier, aerial refueling can extend the endurance of an aircraft to the endurance limits of the crew, but unmanned aircraft remove this crew limit on endurance. Therefore, extreme-endurance UAVs could be realized by multiple cycles of aerial refueling. However, other approaches to extreme endurance are also possible. For example, HALE vehicles, lighter-than-air vehicles, or solar-powered aircraft based on earlier development work funded by DARPA and the Missile Defense Agency (MDA) and subsequently further developed by the National Aeronautics and Space Administration (NASA)[4] can fly for extended periods of time. This type of UAV has demonstrated flight near 100,000 ft. Endurance is limited to about 12 hours because of a lack of suitable onboard energy-storage systems. However, the addition of pressurized gaseous hydrogen/air fuel cell systems can extend endurance initially to 30 hours, and eventually to 2 weeks, with cryogenic hydrogen storage. Further extensions in endurance would be possible with a regenerative fuel cell system now being researched, making possible continuous flight for months or even longer.

Advanced Sensors Combined with UAVs

The application of advanced sensor techniques combined with UAVs could provide new mission capabilities or enhance current ones. For example, the problem of sensing and identifying vehicles under camouflage or under a tree canopy is not satisfactorily solved. Advanced optical techniques combined with a small, offboard sensor UAV flying just above the tree canopy or a small UAV flying under the tree canopy could substantially improve this capability. Another useful capability would be that of tracking vehicles for extended periods after they are initially identified as being of interest. A micro-UAV or small UAV might be able to affix passive radio-frequency (RF) tags to vehicles for subsequent tracking or attack.

Optionally Piloted Air Vehicles

Optionally piloted air vehicles are designed to be flown by a pilot onboard, to be teleoperated by an operator on the ground, or to fly autonomously. There are

[4]For additional information, see the Web site <http://www.dfrc.nasa.gov/Newsroom/ResearchUpdate/Helios/index.html>. Last accessed on April 5, 2004.

few examples of this type of aircraft, but it would have some advantages, including the option of being operated as a piloted aircraft for ferry missions, payload operator training, and low-risk missions. The optionally piloted air vehicle could be operated without a pilot for high-risk or long-endurance missions.

Reduction of Costs

High-Risk Strike Mission—Reusable Platform

The inherent benefit of using unmanned vehicles (e.g., cruise missiles) in high-threat environments, without risk of loss or capture of crews, is well recognized. However, the ability to accomplish this class of missions using reusable platforms (UAV and UCAV) has significant potential benefits. Even though reusable air vehicles need to be launched, recovered, and serviced between missions, it is likely that such operations can be sustained at much lower cost than that for expendable strike systems such as cruise missiles. The main elements contributing to AV systems costs are operations and support, training, and system development and procurement.

Operations and Support

Although early expectations were that UAVs would return cost savings across all life-cycle cost elements, experience has shown that the greatest potential savings will be in operations and support (O&S) costs. As indicated by the examples in Table 4.1, the single largest contributor to O&S costs of any manned system typically is driven by the number of direct and indirect personnel required to support and operate it. UAVs have potential, albeit yet unrealized, to reduce those costs. The mechanisms for achieving this potential, however, are often more operational than technical. For example, reach-back (i.e., relying on personnel based away from the operational theater) can reduce the number of forward-deployed personnel. Changing the way in which operator proficiency is qualified and maintained, as discussed below, is another method for reducing O&S costs. Technical solutions for reducing personnel-related O&S costs include employing greater levels of autonomy to reduce overall personnel requirements. It is important that naval leadership emphasize advances in both operational and technical areas to ensure that the O&S cost-saving potential of UAV operations is realized.

Training

Whether for manned or unmanned air vehicles, O&S costs are typically driven by peacetime requirements for flight training hours. The DOD's 2002 UAV Roadmap, for example, estimates that 50 to 90 percent of total flying hours

TABLE 4.1 Primary Operations and Support Cost Drivers—Manned Aircraft Examples

Primary Cost Drivers	Percentage of Total
USAF F-16 C/D Active ACC, PACAF, and USAFE[a]	
Mission personnel plus personnel-related indirect costs	39.6
Depot-level repairables (DLRs)	32.9
Petroleum, oil, and lubricants/energy consumption	9.8
Depot repairs other than DLRs	8.4
Consumable supplies	4.6
USN F-18C Active Less Fleet Reserve Squadron Training Costs[b]	
Organizational personnel costs	26.3
Aviation DLR costs	22.8
Fuel costs	15.1
Intermediate costs	7.1
Depot support costs	5.9

[a]See <http://www.safaq.rtoc.hq.af.mil/f-16.cfm>. Last accessed on March 31, 2004.
[b]Information from <http://www.navyvamosc.com/>. Last accessed on April 7, 2004.
NOTE: C/D, version or model of F-16; ACC, Air Combat Command; PACAF, Pacific Air Force; USAFE, U.S. Air Force in Europe.

are on peacetime training sorties and that this is an area in which UAVs can achieve savings in comparison with manned systems. One reason for such savings, for example, is that UAVs are more automated than manned aircraft are, and the training-hour requirements are correspondingly less. An experienced USAF Predator operator is required to fly 18 training sorties per year to maintain required proficiency, whereas an experienced USAF U-2 pilot is required to fly more than four times as many training sorties.

Another potential area for training-hour reduction is to rely more on simulation for UAV flight training. The remote operating environment and displays/cues involved in UAV operation are easy to replicate in simulation, and actual flight-hour requirements could be reduced even further by employing such aids. One area, however, that will not be as amenable as other UAV operations are is that of carrier operations. Even with automation, it is likely that operator proficiency will continue to rely heavily on actual flight operations rather than on simulation to develop and maintain operator and deck crew skills, particularly for launch and recovery.

System Development and Procurement

Because UAV development is still in its infancy, there has been little opportunity to benefit from what could be a significant downstream cost saving derived from compatibility and reuse of common development items such as communications, control stations, and payloads. Even though efforts to standardize control stations and communications across naval UAV systems have not yet achieved unqualified success, the overall concept still has considerable merit. In the future, however, trends indicate that the commonality approach will change from its current focus on hardware and software to focusing on common and open architectures and combinations of the two.

TECHNOLOGY ISSUES AND NEEDS

Despite unmanned aerial vehicles' impressive range of capabilities and potential benefits for naval operations, some important capabilities must be addressed if the full potential of these vehicles is to be realized in a timely fashion. Some of these needed capabilities are current impediments to timely progress, while others simply reflect current levels of maturity.

Fundamental Unmanned Aerial Vehicle Issues

Communications and Bandwidth

By their very nature, UAV operations depend on secure, reliable, and available communications. Although autonomy and other technology developments can minimize communications bandwidth requirements, regular downlink communication is still required for sensor data and information on vehicle status, position, and system health. Although continued system and technology development is expected to make progress in this area, the dependency itself will not go away. Continued attention to this subject, therefore, is essential (see Chapter 7, the section entitled "Unmanned Aerial Vehicle Communications," and Appendix B).

Positive Automatic Target Recognition

Current UAV CONOPS typically depend on RF-based synthetic aperture radar (SAR) sensors with or without ground moving target indicator (GMTI) capabilities to provide overall battlefield situation awareness. Under current rules of engagement, however, target identification using electro-optical/infrared (EO/IR) sensors is generally required in order to have positive target identification prior to authorizing a lethal attack. As a consequence, during periods of poor or reduced visibility or low cloud ceilings, operational tempo suffers. Considerable benefits could accrue, therefore, from systems or technologies that enable the equivalent of EO/IR-based levels of target-recognition confidence using weather-penetrating, RF-based sensors. This is a very fruitful area for research and technology development, and an initiative in this area is recommended. (See Chapter 7 for additional relevant discussion.)

Operations with Manned Air Vehicles

After almost 100 years of operation, military and civil airspace regulations and procedures are well established. However, their current methods of operation are not compatible with the usual operational procedures for UAVs. In civil airspace, the pilot in the aircraft has ultimate responsibility for safe operation of the aircraft and for maintaining safe separation from other traffic. Since UAVs have no pilots in the cockpit, they are having problems fitting into national (military and civilian) and international airspace operating environments. The issues involved are far too complex to address in this study, but it is likely that technology (e.g., automatic collision-avoidance systems) can resolve most of the issues. The eventual solution must be a combination of technology and operational procedures. Fortunately, a number of excellent initiatives are addressing the issue. For example, the UAV National Industry Team (UNITE)[5] is working in conjunction with the DOD, NASA, and the Federal Aviation Administration on UAV-related issues such as certification of UAVs and free access to the national airspace.

Contingency Planning

One of the most important functions of a manned aircraft pilot is to deal with contingencies, including, when possible, safe recovery of the aircraft from an emergency. The issue of contingency planning to avoid or deal with emergencies is fundamental to all air vehicle operations, but it is substantially more complicated for UAVs, and as a consequence can benefit from further technology and capability development. Once again, these issues are being addressed by industry/government groups, but until the issues are resolved—the UAVs will need a perception subsystem to detect other aircraft, a planning subsystem to coordinate flight paths, and so on—UAV contingency-planning considerations will constrain how and where UAVs are allowed to fly.

Intelligent Autonomy Technology—Key to Advanced Autonomous Operations

As UAV operations become more routine and better integrated with those of other aircraft, UAVs will need to fly as part of coordinated operations and in shared airspace. This environment will require autonomous systems for detecting other aircraft, coordinating flight paths to optimize area operations globally and to avoid conflicts. Examples of operations include those in civil airspace, potentially with nonparticipating aircraft in the area (for example, "see and avoid" visual flight rules traffic); takeoff and landing operations at land bases or from

[5]For additional information, see the Web site <http://www.unitealliance.com/faq.html>. Last accessed on April 1, 2004.

carriers, possibly in a mix of UAV and manned aircraft; and in combat operations, cooperative flight with mixed types of UAVs and manned aircraft. Each of these situations would require the UAV to have a level of awareness of other aircraft and the ability to plan and execute flight paths and maneuvers in a complex environment. While in principle it is possible to provide a synthetic environment to a ground-based operator, with a level of awareness similar to that of a pilot in the aircraft, this approach is costly, requires substantial and perhaps unsustainable communications bandwidth, and would defeat the long-term goal of having one operator control multiple UAVs. The most desirable approach would be autonomous UAV systems to manage conflict and collision avoidance and to plan flight paths in cooperation with other air vehicles and elements in the operational environment.

A Systems Approach to Facilitate Autonomous Flight Operations

Current sensor systems for UAVs have been, in general, developed separately and not as part of the overall system. A more systems-oriented approach can provide improved performance not currently possible. In general, sensors are installed in a UAV for self-awareness and for mission performance (e.g., the ISR mission). UAV systems, sensors, and software, conceived and developed as a unified system along with the vehicle design, can allow optimum mission performance. In the hierarchy of levels of autonomy, current UAVs tend to have somewhat limited autonomy; however, they will become more valuable in the future as their levels of autonomy increase. Higher levels of autonomy will provide benefits of reduced operational manning, increased vehicle self-awareness to improve reliability and reduce maintenance, and increased operational capability.

Mission-Dependent Autonomy Management

UAV flexibility and utility would be substantially enhanced by the capability of operating at various levels of autonomy, depending on mission needs. The key to achieving this capability is the development of mission-management software that can perform a mission at various levels of autonomy and interact with the vehicle-management software module and the weapons system-management software module the way that a pilot responds to and tasks those systems today to perform a mission. The vehicle-management module monitors and controls the vehicle's systems in response to commands from the mission module. The weapons system module monitors and controls the defensive and offensive systems and weapons, responds to tasking from the mission module, and tasks the vehicle module as required to complete the assigned mission task. The piece in need of development is the mission module that emulates the mission commander at whatever level of authority (autonomy) has been granted.

Autoland Systems

UAVs have developed a reputation for having a higher loss rate than that of piloted aircraft. A relatively high proportion of the losses occurs during the landing of teleoperated UAVs. Reliable autoland systems have the potential to substantially reduce losses. Although teleoperated conventional runway landing can be quite challenging, landing a UAV on a deck in even moderate sea states can be beyond the capability of a human operator. Autoland systems being developed by several manufacturers and government agencies will be an important addition to current and future UAV systems. For example, the Navy's Joint Precision Approach and Landing System (JPALS)[6] seeks to improve the capability and reliability of the current Automated Carrier Landing System (ACLS) to a level of performance necessary to safely land UAVs, such as the J-UCAS, aboard carriers.

Among the driving factors in carrier integration of UAVs are launch and recovery. The current ACLS is woefully inadequate for UAV employment. The ACLS specification requires less than 1 failure per 100 recoveries, which is adequate when a pilot can override the automated system, but it is orders-of-magnitude higher than tolerable for UAV operations. The current actual ACLS failure rate for UAVs can be on the order of 1 in 3.[7] The JPALS now under development has the potential to meet the requirement for ultrareliable recovery. Its error rate is specified to be 1 in 10 million. Successful fielding of JPALS appears to be a prerequisite for UAV carrier operations. However, JPALS's heavy dependence on GPS is a source of concern. A limited alternate capability based on short-range laser or microwave RF systems would be prudent for cases when GPS is unavailable, if only for a short time. Other alternatives should be pursued.

Data Links and Special Communications Antennas

UAVs would benefit from the development of improved data communications systems to increase data transmission rates and increase the signal flexibility of antennas. Current UAVs such as the Global Hawk and the Predator make significant vehicle configuration compromises in order to incorporate high-gain satellite communications (SATCOM) dish antennas. Further development and incorporation of conformal active-array antennas would benefit the performance of UAVs by avoiding design compromises for large-dish-type SATCOM anten-

[6]For additional information, see the Web site <http://www.hanscom.af.mil/esc-ga/Products/jpals.htm>. Last accessed on April 1, 2004.

[7]Glen Colby, JPALS Chief Engineer, "UCAV-N, Naval Unmanned Combat Air Vehicle, Carrier Integration Challenges, Automatic/Autonomous Flight Operations," presentation to the committee, April 24, 2003.

nas. The use of this class of antennas could allow rapid-beam steering for burst communications with a series of different platforms and therefore facilitate the UAV role as a communications hub in a battlespace network, assist with cooperative operations, and perhaps reduce the likelihood of jamming or interference.

Imagery Processing, Exploitation, and Dissemination Software

A significant mission for UAVs is as one of the military assets for providing timely ISR, particularly persistent ISR. Current airborne and space-based ISR platforms provide an almost overwhelming stream of data. UAVs will introduce additional airborne sensor platforms, and persistent UAV platforms will vastly increase the quantity of data available. However, for this data to be useful, they must be interpreted and analyzed, and important components of the data must be forwarded in a useful form to the end users. This step is now largely accomplished by trained human operators (available in limited numbers) communicating over data links with modest capacity. Intelligent software agents could accomplish some portion of the data exploitation process to relieve the burden on a limited number of analysts and perhaps reduce the quantity of data to be transmitted by eliminating unneeded data (i.e., portions of images that contain no objects of interest or that have not changed from the last image).

Fuel-Efficient, Small-Turbine, and Heavy-Fuel Internal Combustion Engines

The military is switching to less volatile, heavy fuels for all vehicle types in order to reduce logistical complexity and cost and to increase safety. This change results in powering virtually all military vehicles with either turbine or compression-ignition (diesel) engines. Notable exceptions are certain small and medium-sized UAVs that, to achieve low specific fuel consumption (SFC) and long endurance, use aviation gasoline or similar volatile fuel. Although many engine options exist for spark-ignition engines for small aircraft applications, there are few flight-weight diesel engines. This class of UAVs needs heavy-fuel turbines and compression-ignition engines with improved SFC to improve operating characteristics and to better fit in the military logistical system. The development of diesel engines suitable for use in fixed- and rotary-winged UAVs is an area needing attention.

Improved Survivability

Although unmanned, UAVs still represent valuable assets that must be sufficiently inexpensive and plentiful to be considered "attritable" (or dispensable) or else they must be able to survive if their missions require them to operate in hostile areas. Including survivability features in a UAV will generally increase the cost of an individual aircraft. However, survivability could both reduce the overall cost of UAV systems (including the cost of replacing UAVs lost through attrition) and increase their availability during operational campaigns. This trade-off needs to be considered in light of the cost and intended mission of the UAV system.

Many targets in a deep-strike mission may be well defended. In the future, given the availability of high-technology weapons systems and network technology on the open market, it is likely that integrated air defenses of adversaries will be very capable. UAVs will need low signatures to survive, but stealth alone is unlikely to protect an air vehicle that loiters for a significant period of time in view of netted air defenses. Threat-detection-and-response considerations may include provisions for threat cueing by offboard sensors or systems, onboard threat-detection systems, threat-avoidance maneuver algorithms, and active self-defense measures normally employed on manned aircraft. That is, UAVs may need to deploy decoys, launch antiradiation weapons to attack enemy air defense radars, and engage incoming surface-to-air missiles with air-to-air weapons.

In addition to developing methods of employment that minimize the exposure of UAVs to threats, technologies need to be considered from the outset of the design process and applied to UAVs to improve their tolerance to damage and their ability to avoid damage. These protections are provided in manned aircraft by liberal use of redundancy to eliminate critical single-point failures and by incorporating damage tolerance and hardening in the basic design as well as threat-detection and defensive systems. Damage-tolerance considerations include redundancy in structural load paths and features to limit the propagation of damage, aerodynamic designs allowing continued controlled flight with damage to or loss of some airframe elements, and control systems capable of recognizing the loss of control surfaces/actuators or changes to the aerodynamic configuration of the vehicle, compensating or reconfiguring to allow continued flight.

These survivability features need to be incorporated as appropriate, on the basis of trade-off studies of UAV cost, criticality of function, and anticipated threat environment. Such features have been developed in manned aircraft and would be straightforward to adapt to UAVs.

Other Issues Related to Unmanned Aerial Vehicles

Reliability

The history of UAV development includes failed programs that overemphasized low cost at the expense of reliability. In these cost-driven programs, fundamental reliability-driven design philosophies and processes based on years of experience with manned aircraft were not followed. Some low-cost UAVs did not even use qualified aerospace components, and hence these UAVs experienced high in-flight failure rates. These low-cost-driven designs had little or no redundancy, even for flight-critical systems. The end result was high crash rates, in some cases resulting in program cancellation. Fortunately, however, this was

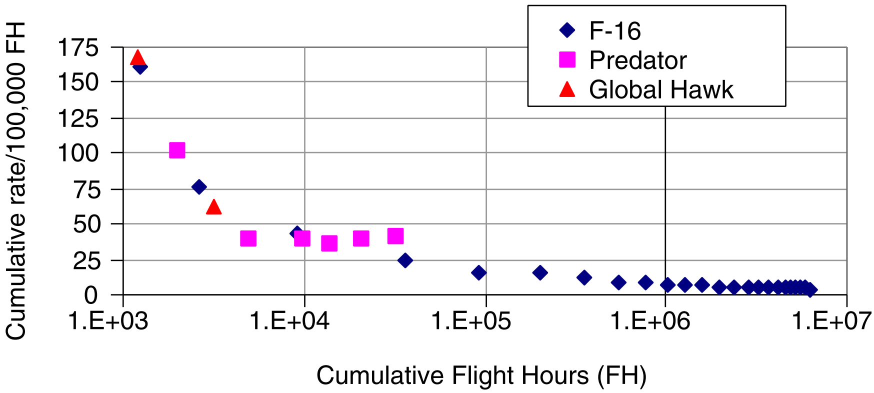

FIGURE 4.10 Class A mishap rate comparison. Predator and Global Hawk Class A accident rates are comparable with those of manned fighters (F-16 during its early development through initial operational deployment) at equivalent cumulative flight hours. SOURCE: Air Force Safety Center, online at <http://afsafety.af.mil/>. Last accessed on March 31, 2004.

not the case for all UAVs. For example, the BQM-34 (Firebee high-speed target drone) family of UAVs was based on traditional aerospace-quality design processes and as a consequence experienced much higher levels of reliability.

Contemporary UAV design philosophy has been much more attentive to reliability and redundancy requirements, and in-flight failures and subsequent mishap rates have moderated. This change can be seen from Figure 4.10, in which cumulative Class A mishap rates for the Predator and Global Hawk are compared with those of an F-16 at the same number of cumulative flight hours. This plot shows that the mishap rates for these UAVs are comparable with those of the F-16 during its early development through initial operational deployment. Therefore, as the Predator and Global Hawk mature and accumulate operational flight hours and experience, they may be able to approach comparable levels of flight safety. Continued emphasis in this area, however, will be essential if the real potential is to be realized.

Program Cost

The costs of system development and procurement are two of the four elements of the life-cycle cost of UAVs. A number of studies, including the DOD's 2002 UAV Roadmap,[8] have shown that for UAVs of capability and complexity

[8]Office of the Secretary of Defense. 2002. *Unmanned Aerial Vehicles Roadmap 2002-2027,* Department of Defense, Washington, D.C., December.

comparable with that of manned aircraft, manned versus unmanned development and acquisition costs are essentially comparable. While this may be attributable to the fact that the industry is much lower on the learning curve with UAVs compared with manned aircraft, early expectations that UAVs could be developed and procured at significantly lower cost than their manned equivalents have not materialized. However, even with UAV experience being relatively immature compared with that of manned aircraft, it has become increasingly clear that the program cost drivers for manned and unmanned aircraft are identical—requirements and requirement stability. Thus, UAV developers need to continue pursuit of UAVs as a lower-cost alternative. In fact, as UAV systems mature, there will be opportunities to significantly reduce overall development and acquisition costs in the future.

Opportunities for Future Program Cost Savings

Because of the fundamentally distributed nature of UAV systems, there will be opportunities for developers of future UAVs to take advantage of existing system components, as opposed to developing new elements that could be optimum for the new applications but at higher development and acquisition cost. In order to achieve this goal, however, it will be essential that naval UAV system architectures be designed to standardized interface requirements at a minimum.

Culture Acceptance

The last but perhaps most important issue affecting UAV deployment in support of naval operations is cultural acceptance. This well-known issue does not need to be further elaborated here, except to note that success breeds success. UAV program decisions, therefore, need to be constantly evaluated from the perspective of their long-term program impact. Shortsighted decisions that adversely affect UAV system reliability, maintainability, and safety could have detrimental effects that extend beyond an individual program. For example, UAV lessons learned have shown that the selection of remotely piloted takeoff and landing can minimize early development cost but result in substantially higher attrition and overall life-cycle costs compared with those for automated takeoff and landing.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions and recommendations based on the preceding UAV background and discussion are presented in the following subsections.

Conclusions Concerning Unmanned Aerial Vehicles

UAVs Have Come of Age

In assessing the UAV situation today, the committee believes that the United States has made considerable progress over the past 3 to 4 years in moving to exploit the potential offered by unmanned air systems. Little doubt remains as to the operational utility and military worth of UAVs. They have proven themselves in combat, and warfighters want them, particularly since UAVs are now seen as essential to realizing the all-important persistent surveillance of the battlespace. UAVs have indeed come of age at last and are destined to play an increasingly important role in future years for ISR, strike, and other key military missions. Also, it appears that UAVs have strong support in the Office of the Secretary of Defense, among the unified combatant commanders, and with members of Congress. Accordingly, the Naval Services need to capitalize on the current positive climate and move out with dispatch to exploit the momentum that has been established.

Navy and Marine Corps Behind Other Military Services in Fielding Modern UAV Systems

Despite recent advances, UAVs are still not widely distributed across the military Services or firmly integrated into Service force structures. Also, funding support is at times tenuous. Overall, the pace of introduction of UAVs has been slow to date; indeed, as of early summer 2003, only 130 UAVs of Pioneer/Shadow-size or larger were operational throughout the DOD, with the Navy and Marine Corps significantly behind the other Services in numbers and in fielding modern systems.

There are manifold reasons for this slow pace of introduction and utilization of UAVs, with some key areas as follows:

- *Culture and policy.* The culture of any large institution of long standing almost always militates against ready acceptance of new concepts or, in the case of the military, against new weapons systems. The Navy is not immune to the effects of this phenomenon.
- *Competition with legacy and other new systems for funds.* As a relatively new type of military weapon system, UAVs are in competition for funds with older systems or even with other new systems that are viewed as frontline mainstays of a Service's force structure. The Navy, for example, has a number of high-cost platforms—aircraft, submarines, aircraft carriers, surface combatants, amphibious ships—all of which are seen as key elements that make up the "core" of the Service. Replacing aging ships and aircraft, provisioning them with weapons, and paying for operations and maintenance constitute a heavy financial burden.

In such an environment, it is often the case that a new kind of system, such as UAVs, remains at the bottom of the priority list.

- *The program start-stop-start syndrome.* The unfortunate practice of starting a military program and then, when production is about to commence, canceling it in favor of a supposedly more promising system, has plagued the UAV world for years. Each such sequence adds years of delay in equipping the operating forces with UAVs. Past program examples include the Navy/Marine Corps Amber, the Hunter Short-Range UAV, the Mid-Range UAV, and the first joint tactical unmanned aerial vehicle (TUAV) program. And currently, production and fleet introduction of the already-developed Fire Scout are in jeopardy.
- *Greater than expected costs, high accident rates, unreliable systems, and combat survivability concerns.* A reason often given in the past for a military Service's not making a strong commitment to UAVs is that these new systems cost more than anticipated, suffer from high accident rates because of subsystem unreliability and operator error, and lack the combat survivability features of manned aircraft. These concerns are valid, but all are solvable if the requisite attention is paid to them.
- *Reluctance of one military Service to use the UAV system of another.* Although this problem may smack of the "not invented here" syndrome, it is an understandable characteristic of some validity. A commander feels most secure in owning and completely controlling a system that is fundamental to accomplishing the command's mission. But there are obvious cost and operational advantages for the DOD if multi-Service use can be achieved—overall system development costs are reduced, and UAV force levels can be increased more rapidly. Here, "use" is defined in two ways: (1) one Service acquires and operates a system developed by another Service, and (2) in the case of ISR, one Service merely makes use of the information generated by the UAV system of another Service.
- *Radio-frequency bandwidth constraints and lack of interoperability.* The committee believes that radio-frequency bandwidth capacity limitations, interoperability problems, and imagery processing/exploitation issues are near the top of the list of impediments to a more rapid near-term introduction and utilization of UAV systems. Each of the military Services suffers from these constraints to varying degrees, with the Navy's ships at sea and the Army and Marine Corps units at battalion level and below being the most adversely affected.

Both the Army and Air Force are now operating modern UAVs, and the two Services have systems in series production as well. The Navy, on the other hand, has no UAVs in regular production and none in its operating forces. The Marines have some 22 aging Pioneers, a small tactical system developed in the 1980s, and operated them with mixed effectiveness during Operations Desert Storm and Iraqi Freedom as well as during the Kosovo campaigns. Additionally, the Marine

Corps has begun to introduce the small, human-portable Dragon Eye system to serve units at battalion level and below. But in the aggregate, the Naval Services, which once led the Department of Defense in developing and fielding UAVs, are now lagging the other Services in gaining operational experience, developing operational concepts, and exploiting the transformational warfighting potential offered by these unmanned air systems. Absent a dramatically increased involvement with UAVs, the Navy and Marine Corps run the risk of falling farther behind, not fully exploiting the benefits offered by Army and Air Force systems, and lagging in efforts to shape the direction that new UAVs systems will take in the future.

Importance of Accelerating the Fielding of UAVs

The committee found that operational experience with the Predator, Global Hawk, Hunter, and special-purpose UAV systems during recent conflicts demonstrated that, once employed by warfighters, the value of UAVs becomes immediately evident, ideas for new operational concepts are spawned, a constituency is formed, and strong advocacy begins to build. Hence, an important strategy to increase involvement by the Naval Services with UAVs is to accelerate the introduction or exploitation of those systems that are in production or have completed development and are judged to have significant operational utility. To this end, the committee concludes the following:

- Requirements generation is best approached from the perspective of mission needs and effects versus that of platform ownership or base location,
- Procurement or employment of UAVs developed by the Air Force and Army is an essential ingredient of plans to introduce UAV systems capabilities more rapidly into the Naval Services, and
- Essential enhancements to command, control, and communications (C3) and information-exploitation systems need to be made concurrent with accelerating the introduction of already-developed UAV systems into the fleet and Fleet Marine Force.

Naval UAV Roadmap Lacking in Detail and Not Sufficiently Forward Looking

The Navy and Marine Corps have a naval UAV roadmap[9] in place. However, the roadmap has been slow to evolve and, in addition, it does not address advanced technology needs or issues between the two Services regarding the use of tactical UAVs.

[9]Department of the Navy. 2003. *U.S. Naval Unmanned Aerial Vehicle Roadmap 2003,* Report to Congressional Appropriations Committees, U.S. Government Printing Office, Washington, D.C., March.

Navy's Views on Its UAV Future. The Navy views its future use of UAVs to be in primarily three categories:

- Long-dwell standoff ISR as exemplified by the Broad Area Maritime Surveillance (BAMS) concept and the Global Hawk Maritime Demonstration (GHMD);
- The carrier-based, penetrating surveillance and suppression of enemy air defense (SEAD)/strike J-UCAS; and
- Ship-based tactical surveillance and targeting, which call for a vertical-takeoff-and-landing (VTOL) system that can operate from a variety of types of ships.

In reviewing the Navy's progress toward realizing this three-category future for UAVs, the committee noted that the DARPA/Navy UCAV-N ATD has transitioned into a combined effort with the Air Force along the lines of the Joint Strike Fighter program. The committee endorses the J-UCAS program as presently planned and urges that Service leadership strongly support this promising initiative.

Long-Dwell Standoff ISR System. The road ahead seems unclear for the long-dwell standoff ISR system. To begin with, the committee noted the near-concurrency of the GHMD and contract award for the BAMS UAV, and thus it remains concerned that lessons from the Global Hawk demonstration might not be reflected in the BAMS program. The BAMS development also appears to be a technically challenging and lengthy process, and HALE UAV support to naval forces will not be available to the fleet until 2009 at the earliest, unless provided by the Air Force. Further, this development is to take place concurrently with spiral development improvements to the Air Force Global Hawk system. That system, like the Navy BAMS, will require considerable research, development, testing, and evaluation investment.

This concurrency offers the potential for a joint program with the Air Force for the acquisition and operation of a common system that would meet both overland and maritime needs. The potential exists for reduced development costs to the Navy and to the DOD overall, as well as the opportunity for greater operational flexibility for regional combatant commanders. Part of such an approach would also be to increase the annual Global Hawk production rate, with a resultant reduction in air vehicle unit production costs for both Services. A similar opportunity for a joint development and operations arrangement with the Air Force would exist if Predator B were selected for the Navy BAMS mission.

Ship-Based Tactical Unmanned Aerial Vehicles. At present the Navy has no ship-based TUAV capability, and there is no formal acquisition program for

TUAVs in the Future Years Defense Program (FYDP). There are, however, plans that link the Fire Scout VTUAV (vertical-takeoff-and-landing TUAV) with the nascent Littoral Combat Ship (LCS) as the latter begins to enter operational service after 2007. Here the committee is concerned that the introduction of a sea-based tactical surveillance and targeting capability in the fleet, which could begin with the Fire Scout as early as 2005, now appears to be tied to the development of a new ship class not scheduled for initial operating capability until after 2007.

The committee also notes that the current plan for the Fire Scout does not include ships other than the LCS. Thus, Navy ships at sea, including those in Expeditionary Strike Groups (ESGs) and embarked Marine Air Ground Task Forces (MAGTFs), will continue to lack organic ISR UAV capability at least through this decade, and will have to depend wholly on imagery garnered from limited, manned fighter reconnaissance systems, national overhead systems, and Air Force ISR systems such as the Global Hawk, Predator, U-2, Rivet Joint, P-3 Antisurface Warfare Improvement Program (AIP), and Joint Surveillance Target Attack Radar System (JSTARS). Equally important, naval forces at sea will be denied the opportunity of working directly with a modern ISR UAV system to gain operational experience, develop employment concepts, and formulate operational requirements for future systems. It therefore appears to the committee that the Naval Services will continue to suffer from a serious ISR deficit at least through 2010, during which time the Army and Air Force will continue to develop operational concepts and gain valuable experience that will lead to improved UAV systems in the future.

Marine Corps's Views on Its UAV Future. The Marine Corps envisions three levels of UAV support for its warfighters operating from the sea or ashore in Marine Air Ground Task Forces, which range in size and capability depending on the mission (MAGTFs might consist of Marine Expeditionary Units (Special Operations Capable), Marine Expeditionary Brigades, or Marine Expeditionary Forces). At the theater level, the MAGTFs will rely on national systems as well as on information derived from the Global Hawk and Predator, currently Air Force assets. In addition, they will require data and imagery from other ISR platforms such as the U-2, JSTARS, Rivet Joint, and the P-3 AIP, as available.

At the tactical level, the Marine Corps plan is for MAGTFs to continue relying on the Pioneer for operations ashore until it is replaced by a tactical UAV system suitable for use from both sea and land bases. This future system will operate from amphibious assault ships (LHD (amphibious assault ship, multipurpose), LHA (amphibious assault ship, general purpose), and LPD (amphibious transport dock)-17 classes) within the ESG or from a future class of sea base ships, and also from land when operationally required. If a need for TUAV support arises in circumstances in which no organic TUAV assets are available to the MAGTF but the Marines are operating in the vicinity of the Army, the plan is to coordinate support from Army UAV systems such as the Hunter and Shadow 200, as was done successfully during Operation Iraqi Freedom.

At the lower tactical-unit level (battalion, company, or platoon), the Marine Corps's tactical UAV need is to be satisfied by the human-portable Dragon Eye UAV system. The Dragon Eye was employed on a limited basis in the recent drive on Baghdad, with reasonable results for a system still under development.

Navy and Marine Corps Views on TUAVs. Navy and Marine Corps views on UAVs diverge over the issue of tactical UAVs. Responding to an earlier Naval Services' requirement, the Fire Scout VTUAV was developed and is now completing acceptance tests. While the Fire Scout's performance exceeds the original joint requirement, the Marine Corps now believes that the system does not meet the needs of its future vision of deep-penetration, Ship-to-Objective Maneuver tactics, which will capitalize on the high-speed V-22 Osprey tilt-rotor troop transport. The Marine Corps, therefore, is looking at the U.S. Coast Guard Eagle Eye tilt-rotor development as well as at other systems as potential candidates for their combination of VTOL capabilities and high cruise speed. While somewhat slower than the V-22 Osprey, the Eagle Eye is nevertheless considerably faster than the Fire Scout.

The Fire Scout and Eagle Eye offer the same endurance and similar sensors, and each is limited to a line-of-sight communications range. Hence, other than speed, the principal difference between the two VTUAVs is readiness for production. The Fire Scout is a fully developed system ready for production; units could be in the fleet within 20 months of a production go-ahead. The Eagle Eye, on the other hand, is a developmental system, and the Coast Guard schedule shows the system reaching initial operating capability late in 2007.

Current Marine Corps thinking on what constitutes a suitable VTOL tactical UAV points to a system more closely matching the V-22 Osprey in speed, with range out to 200 nautical miles. This higher performance is desired in order to facilitate surveillance and screening operations out in front of the V-22 Osprey, and with the control of the UAV being exercised from the Osprey. Such a requirement would call for a VTOL air vehicle larger than the current Eagle Eye, one likely equipped with SATCOM as well as sensors other than EO/IR, and possibly with weapons. Hence, if selected by the Marine Corps, a tilt-rotor-like VTOL UAV will realistically be viewed as the first of a line of high-speed unmanned rotorcraft, likely employing tilt-rotor or tilt-wing technology. To date this emerging Marine Corps VTOL UAV need has yet to be defined with any precision, including conduct of the required detailed Analysis of Alternatives.

The Navy, for its part, is sensitive to the needs of the Marine Corps and indeed has indicated preliminarily that in a few years' time, it may wish to revisit the sea-based tactical UAV requirement together with the Marine Corps. Further, the two Services agree that, from an affordability and operational flexibility perspective, a single ship-and-shore-suitable tactical UAV system, meeting both Navy and Marine Corps needs, is the correct path for the future.

Introduction of Ship-Capable TUAVs Without Further Delay. The committee believes that ship-capable TUAVs need to be introduced into the Naval Services without further delay. And since the Fire Scout is the only such system currently available, the Navy can therefore move immediately to acquire a small force of Fire Scouts to develop operational concepts and tactics, help formulate requirements for future systems, and provide a sea-based ISR UAV contingency response resource. Further, to facilitate an accelerated introduction of the Fire Scout into the fleet in 2005, a VTUAV tactical development squadron should be formed by the Navy and the Marine Corps, and the Coast Guard invited to participate. Since the Army has selected the Fire Scout for its Future Combat System, the Army needs to be invited to participate as well.

A small procurement of the only sea-based tactical UAV currently available, the Fire Scout, would not in any way preclude the Navy and Marine Corps from later selecting the Eagle Eye, a growth tilt-rotor variant, or other suitable VTOL system as the principal sea-based tactical UAV of the future. But to delay now would risk lengthening the sizable current ship-based ISR UAV gap. Notwithstanding what the choice for a future sea-based tactical UAV may be, the experience gained near term with the Fire Scout and its ground station, modern sensor and data link, ship-deck retrieval system, and its automatic landing capability would be directly transferable to any subsequent future system. There appears to be little or no planning for UAVs or other kinds of unmanned systems onboard the LCS, especially in terms of the logistics requirements needed to support those vehicles. Also, the current TUAV requirements for the future destroyer (DD(X)) program exceed those capabilities of the current Fire Scout.

Finally, the committee concludes that the Naval Services should begin the selection of a growth VTUAV capability, which may include a tilt-rotor variant, or other suitable VTOL systems under development by DARPA (e.g., A-160 Hummingbird, unmanned combat armed rotorcraft, or canard rotor wing), as the principal, sea-based tactical UAV of the future.

Recommendations Concerning Unmanned Aerial Vehicles

Recommendation: The Navy and Marine Corps should aggressively exploit the considerable warfighting benefits offered by autonomous vehicles (AVs) by acquiring operational experience with current systems and using lessons learned from that experience to develop future AV technologies, operational requirements, and systems concepts. Specifically:

Accelerate the Introduction of Unmanned Aerial Vehicles. The Navy and Marine Corps should accelerate the introduction, or fully exploit the capabilities, of those unmanned aerial vehicle (UAV) systems of all of the military Services that are now in production or through development and judged to have significant operational utility, such as the Global Hawk, Predator, Shadow 200, Fire Scout, and Dragon Eye. Concurrently, the two Services should move vigorously to eliminate or significantly mitigate deficiencies in the equipment and infrastructure of command, control, and communications (C3) and imagery-exploitation systems that limit the use of the aforementioned UAV systems. It is important for the naval operational community to develop the operational concepts and create the operational pull necessary to accelerate UAV introduction.

Develop a Long-Dwell, Standoff Intelligence, Surveillance, and Reconnaissance Unmanned Aerial Vehicle System. The Navy should aggressively pursue the development and fielding of a long-dwell, standoff intelligence, surveillance, and reconnaissance (ISR) UAV system along the general lines of the Broad Area Maritime Surveillance (BAMS) concept and should formally join with the Air Force to develop, procure, and operate a common high-altitude, long-endurance UAV system suitable for both overland ISR and BAMS maritime missions. In their joint approach, the two Services should increase the system production rate above that now planned in order to realize operational and cost benefits. They should also explore the potential for a joint arrangement with the Department of Homeland Security and its agencies. The current EA-6B (Prowler aircraft) program should be considered as an initial Memorandum of Agreement model.

Evaluate a Vertical-Takeoff-and-Landing Tactical Unmanned Aerial Vehicle (VTUAV) System on an Accelerated Basis. The Assistant Secretary of the Navy (Research, Development, and Acquisition) should support a limited procurement of Fire Scout systems to provide the fleet in the near term with a modern, automated, ship-based, vertical-takeoff-and-landing UAV for developing operational concepts and requirements for a future naval VTUAV system and to serve as a contingency response resource. To facilitate the accelerated introduction of the Fire Scout into the fleet in 2005, a VTUAV tactical development squadron should be formed by the Navy and the Marine Corps, and the Coast Guard should be invited to participate. Since the Army has selected the Fire Scout for its Future Combat System, the Army should be invited to participate as well.

Develop Future Sea-Based Tactical Unmanned Aerial Vehicle Requirements. The Navy and Marine Corps should jointly develop requirements for a future sea-based tactical UAV system that will meet the needs of the Marine Corps's Ship-to-Objective Maneuver concept afloat and ashore and is suitable for employment on a variety of ship types—the Littoral Combat Ship (LCS) and future destroyer (DD(X)) as well as current surface combatants and amphibious ships. The requirements should reflect lessons gleaned from future Fire Scout operations as well as developments of the Coast Guard's Eagle Eye, the Defense Advanced Research Projects Agency/Army A-160 long-endurance helicopter, and other advanced vertical-takeoff-and-landing concepts. In addition, those requirements should flow down to address the maintenance concepts and logistics needs of UAVs, as well as those of other unmanned systems, onboard various future ship types, including the LCS, DD(X), amphibious ships, and the ships of the Maritime Prepositioning Force (Future), which will form the core of the new Sea Basing concept.

Revisit and Strengthen the Unmanned Aerial Vehicle (UAV) Roadmap. The Chief of Naval Operations (CNO) and the Commandant of the Marine Corps (CMC) should assign responsibility for the review and revision of the naval UAV Roadmap to establish a clear plan to address advanced technology needs and the timely introduction of new UAV capabilities and to resolve tactical UAV issues between the two Services.

Establish a Joint Services Unmanned Aerial Vehicle Forum. The CNO and the CMC should together recommend to the Commander, Joint Forces Command, that a joint-Services annual forum be established. The forum should encourage interaction between UAV developers and operators of all of the military Services, resolve interoperability issues, and identify new warfighting capabilities for UAVs that may be applicable in urban and littoral warfare environments. A key task should be pinpointing missions that might be executed more effectively and economically by UAVs and formulating system requirements to meet those needs. Where appropriate, and in situations in which needs cannot be met by other means, the forum should recommend what new UAV developments need to be initiated. The forum should also foster experimentation and should formulate and recommend operational and technical experiments involving UAV systems, including collaborations of UAVs with manned vehicles.

Foster Flight of Unmanned Aerial Vehicles in Controlled Airspace. In concert with the other military Services, the Secretary of the Navy should work to ensure that the Department of Defense is actively supporting initiatives that will lead to safe, unrestricted flight by UAVs in the U.S. National Airspace System, in international controlled airspace, and in combat theaters.

Recommendation: The Assistant Secretary of the Navy for Research, Development, and Acquisition (ASN(RD&A)) and the Chief of Naval Research (CNR) should direct the Navy and Marine Corps Systems Commands, the Office of Naval Research (ONR), and the Marine Corps Warfighting Laboratory (MCWL) to partner with the operational community and monitor the concepts and development of critical autonomous vehicle-related technologies considered essential to the accomplishment of future naval missions. The progress of these developments should be tracked year to year. Specifically:

Pursue New Unmanned Aerial Vehicle Concepts and Technology Developments. The ASN(RD&A) should ensure that the respective Services monitor promising new unmanned aerial vehicle (UAV) concepts and developments, including the Defense Advanced Research Projects Agency (DARPA)/Air Force/Navy Joint Unmanned Combat Air System (J-UCAS), the A-160 Hummingbird, Eagle Eye, X-50 Dragonfly canard rotor wing, unmanned combat armed rotorcraft, organic aerial vehicles, and micro-UAVs. Particular attention should be paid to the DARPA/Army/Special Operations Command A-160 long-endurance rotorcraft program and the Coast Guard's Eagle Eye tilt-rotor development, since these systems offer promise as potential long-dwell intelligence, surveillance, and reconnaissance (ISR) and short-range tactical UAVs, respectively, as well as the DARPA/Air Force/Navy J-UCAS Advanced Technology Demonstration that is developing a stealthy, long-endurance, carrier-based, unmanned combat armed rotorcraft suitable for ISR, suppression of enemy air defense, and strike missions.

The ASN(RD&A) and the CNR should ensure that the Naval Air Systems Command, ONR, and MCWL, in coordination with the Army, Air Force, and DARPA, monitor the need for, progress, and development of technologies that would help realize more effective UAV systems to accomplish future naval missions. At a minimum, the following technologies should be considered in this context:

- Dependable and secure communications, including bandwidth and latency;
- Positive automatic target-recognition and image-processing software;
- Automated contingency planning;
- Intelligent autonomy;
- Systems-oriented flight operations;
- Autoland systems;
- Fuel-efficient, small-turbine, and heavy-fuel internal combustion engines; and
- Survivability features.

In addition, a number of advanced UAV concepts should be continually evaluated, including the following:

- Operations in dirty environments;
- Autonomous aerial refueling;
- J-UCAS for combat air patrol, airborne early warning, and close air support;
- Very small UAVs;
- Deployment of ground sensors from UAVs;
- Aerial release and redocking of UAVs;
- Extreme-endurance systems;
- Advanced sensor combined with UAVs; and
- Optionally piloted air vehicles.

5

Unmanned Surface and Undersea Vehicles: Capabilities and Potential

INTRODUCTION

The environment of the world today reflects increased uncertainty about origins of threats, possible locations of attacks, and means by which they might be delivered. The term "asymmetric threat" is now familiar in the lexicon, and terrorist actions are a frequent occurrence. For naval forces, the classical terms "blue water" threat and "major threat axis" no longer hold the significance they once did. The threat environment has moved from the "blue water" to "brown water," or littoral regions, placing emphasis on power projection, force protection, and expeditionary operations in littoral areas.

Along with this change in emphasis, new capabilities will be required of naval forces in the areas of maritime intelligence, surveillance, and reconnaissance (ISR); oceanographic bathymetric surveys; battlespace preparation; battlespace awareness; mine warfare; antisubmarine warfare (ASW); special operations and strike support; surface warfare (including interdiction); littoral ASW with emphasis on diesel submarines; and base and port security. Particular areas of weakness that have been identified with respect to the needed capabilities include organic mine countermeasures, littoral ASW, and defense against small boats.

In turn, the kinds of missions listed above place a premium on integrated, persistent ISR; command, control, and communications (C3); and distributed, real-time knowledge. The increasing needs arising from the new threats may be alleviated, to a growing extent, by exploiting the benefits of unmanned systems, leveraged by networking sensors and communications to the greatest possible advantage, and using unmanned surface vehicles (USVs) and unmanned undersea vehicles (UUVs) as nodes in sensor and communications networks.

This chapter discusses the following topics: potential of USVs and UUVs for naval operations, the USVs and UUVs currently available or under development, naval operational needs and technology issues, and opportunities for improved operations. The committee's conclusions and recommendations concerning USVs and UUVs are then presented.

THE POTENTIAL OF AUTONOMOUS UNDERSEA AND SURFACE VEHICLES FOR NAVAL OPERATIONS

Unmanned underwater vehicles already play a significant role in naval warfare—the most obvious example being the torpedo. In recent years, several developmental systems have reached levels of maturity at which they can be used in direct support of combat operations. The principal mission of these systems is reconnaissance—to provide environmental or countermine data.

Advantages of Current System Developments

Typically, USV and UUV systems provide significant standoff and clandestine capability. They can operate in fully or partly autonomous modes, but when operating autonomously they do not currently have adaptive or intelligent capabilities. They can carry out predetermined missions, providing optical or acoustic imagery and physical environmental data—such as information on temperature, salinity, depth, and currents, as well as optical properties. As the development of adaptive, and eventually intelligent autonomous, control capabilities become more mature, the potential for these systems to engage in cooperative autonomous behavior will grow, allowing groups of these vehicles to operate together as robust, fault-tolerant, and adaptive networks.

Both UUVs and USVs offer the potential for significant contributions to the conduct of naval warfare tasking, particularly when integrated with one another and with other manned and unmanned platforms, sensors, and communications nodes into a total FORCEnet system solution. The Department of Defense (DOD) and the Navy have recognized the utility of unmanned systems in recent operations, including Operation Enduring Freedom and Operation Iraqi Freedom, and in a number of fleet exercises as well. The Department of the Navy has an outstanding roadmap for the development of UUVs and is well along the path to their production and deployment. In addition, the Navy is currently evaluating the role of USVs, which at present do not have a history of operational experience comparable to that of UUVs.

Needs, Issues, and the Future Potential of Unmanned Surface Vehicle and Unmanned Undersea Vehicle Systems

The Navy's UUV Master Plan[1] identifies the utility of UUVs for maritime reconnaissance (passive electromagnetic/electro-optical (EM/EO) localization, and indications and warning), undersea search and survey, communication and navigational aids, and submarine track and trail. Plans and programs are under way to distribute the sensing and countermeasure assets, building on the early Mk 39 (Expendable Mobile Antisubmarine Warfare Training Target System) (which reached initial operating capability (IOC) in 1994), through the Remote Environmental Monitoring Unit System (REMUS) semiautonomous hydrographic reconnaissance vehicle (which reached IOC in 2002), the Near-term Mine Reconnaissance System (deployed on selected submarines from 1998 to 2003) that is now planned to transition to the Long-term Mine Reconnaissance System (IOC in 2005), the mission reconfigurable UUV (IOC in 2008), to the large displacement mission UUV (IOC in 2011), and, perhaps even larger conformal vehicles releasing swarms of small UUVs. Several key elements are the concept of "families" of vehicles, modularity of vehicle components, energy sources, sensors and payloads, and common architecture (including physical interface) standards. These approaches should facilitate integration into an end-to-end system solution.

To date, much of the UUV development has been platform-centric, with integration often limited to physical interfaces. Today's systems are described by NAVSEA PMS 403 (Unmanned Undersea Vehicle Program Office in the Naval Sea Systems Command) to be the development of a number of "stovepiped" systems leading to the production of similarly stovepiped systems. Future developments need to embody the desired system functionality, standardized interfaces, and common architectures for communications and control, and provide for options to facilitate logistics for extended performance (such as energy pallets or docking stations on the seafloor), sensor fusion (cooperating with other systems), onboard processing, fusing data into information, and compressing the result for communication to other vehicles (manned or unmanned) or the fleet.

Undersea operations, including the difficulty of communications, demand "work-arounds" in the near term as well as further research into increasing underwater communications capabilities. One such step is increased autonomy, which in itself serves to reduce communications needs. Also, a premium is placed on the ability to navigate and to coordinate positions and time lines in order to fuse the data from sensors. One potential solution to the latter two issues may be to release

[1]Program Executive Office for Undersea Warfare (PEO (USW)) and PMS-403 (Program Manager, Naval Sea Systems Command, for Unmanned Vehicles), Department of Defense. 2000. *The Navy Unmanned Undersea Vehicle (UUV) Master Plan,* U.S. Government Printing Office, Washington, D.C., April 20.

small, tethered modules to the sea surface either for radio transmission through the atmosphere or to obtain a Global Positioning System (GPS) navigational fix.

It is important to approach future systems developments and their integration with joint and theater assets (whether organic or not) with an overarching approach to systems engineering and systems management, reflecting integrated concepts of operations (CONOPS). One such example could be the development of a relatively large UUV, capable of sonar mapping for search and classification and capable of deploying a variety of unattended sensors, both tripwire and other varieties (for example, acoustic or magnetic to determine ship movements to and from port areas of interest). The example UUV would also be capable of certain revisit rates to download information from such sensors and provide restorative power, as needed, to the sensors (particularly if the sensors include a significant amount of onboard computational capability). By the same token, the UUV may be able to recharge its energy from an energy pallet or source previously placed on the seafloor by another large UUV, ship, or aircraft. To complete the picture, the UUV may be able to obtain data from companion USVs performing maritime reconnaissance tasks, deploy a small buoy or antenna to the surface to gain GPS and timing updates, provide onboard processing to fuse the results, and, finally, deploy another small buoy or antenna providing a burst transmission to either a satellite or unmanned aerial vehicle (UAV) communications relay, thereby allowing the Navy to enjoy a persistent, real-time alert-and-warning capability. If necessary, and if endowed with enough energy, the large UUV could initiate a track-and-trail operation, then accomplish a handoff to another companion UUV to track, trail, or tag the target.

Naval operations in the air, at the sea surface, and in the ocean need good information about the environment. For example, knowing the acoustic environment in the upper ocean enables the prediction of the performance of sonar sensors. Similarly, knowing the presence of bioluminescent organisms in a nearshore area could predict difficulty for a Special Operations Force or mine countermeasure activity. This kind of knowledge and understanding of the environment is an essential component of technological superiority.

It has been the hope that numerical modeling, particularly coupled to ocean atmosphere modeling with sparse in situ and remotely sensed data, would provide high-resolution, accurate environmental fields to guide tactics and strategy. While the development of these models and the techniques for data assimilation are still an active research area, so are the needs for accurate data in both the atmosphere and the ocean. These data cannot be provided by remotely sensed, overhead assets but require direct, in situ measurements. The difficulty of providing sufficiently accurate and well-resolved data in the ocean has been faced by the research community as well, aggravated by the rising cost of ship time. The answer has been autonomous vehicles.

Many of the small UUVs in use today were developed under support from the Office of Naval Research (ONR) in order to address these environmental sensing needs. These systems are sufficiently robust and well developed at this point to contemplate the larger question of whether they can be used cooperatively with numerical models to characterize an ocean environment. For example, the ONR-sponsored program (July 2003) on the Autonomous Ocean Sampling Network (AOSN) in Monterey Bay, California, uses a suite of autonomous vehicles as well as many other assets whose sampling patterns can be adapted and guided by a data-assimilating numerical model to improve the performance of the model's representation of the environment and its predictions. This scenario can be readily extrapolated to include atmospheric boundary-layer observations using USVs and UAVs. One could further imagine this capability over the scales of a Carrier Strike Group or Expeditionary Strike Group providing accurate descriptions of the oceanic and atmospheric environments. The ability to bring multiple observational assets together adaptively so that observations can be used to resolve fronts and other evolving small-scale structures will dramatically improve models and representations of the environment.

Simultaneously with the development of various autonomous systems, the Navy has embarked on the development of the Littoral Combat Ship (LCS), which it is anticipated will play a major role in future combat operations. An integrated suite of both UUVs and USVs, as well as other types of autonomous vehicles, such as UAVs, are likely to be important elements within the LCS complement of combat assets. However, to date there appears to have been little or no consideration given to the logistical issues posed by the presence of such vehicles onboard the LCS. Planning for the launch and recovery as well as maintenance and handling space for these systems must become an integral part of the LCS development process.

OVERVIEW OF UNMANNED SURFACE AND UNDERSEA VEHICLES AVAILABLE OR IN DEVELOPMENT

This section provides an overview of the current status of the Navy's programs for utilizing unmanned surface vehicles and unmanned undersea vehicles. Table 5.1 summarizes the characteristics of a number of these vehicles. While USVs and UUVs have much in common, they have many distinct issues as well. Surface vehicles can use radio frequency (RF) for virtually unlimited communications and navigation. In contrast, the communications and navigation environment for undersea vehicles is challenging at best. Significant improvements have been made in underwater acoustic communications in the past decade, and many of these improvements are reaching operational status. As discussed earlier, future developments in autonomous control should provide effective strategies for minimizing the communications reach-back burden of remotely controlled vehicles.

TABLE 5.1 Characteristics of Various Unmanned Surface Vehicles (USVs) and Unmanned Undersea Vehicles (UUVs)

Vehicle	Endurance	Depth (m)	Speed	Weight/ Payload	Dimension	Initial Operating Capability (FY)
USV						
Spartan	8 h	0	>28 kt	2,600 lb	7 m length	TBD
Owl	7.5 h	0	<45 kt	1,100 lb 450 lb	9.7 ft	TBD
Roboski	50 nmi	0	42 kt	460 lb	9 ft	TBD
RMS	17 h	1	>12 kt	4,000 kg	21 ft	TBD
UUV						
SAHRV	6 h @ 4 kt	100	5 kt	36 kg	0.2 × 1.6 m	03
LDUUV	5 h @ 6 kt	200	12 kt	2,450 kg	0.7 × 8 m	13
BPAUV	TBD	300	6 kt	400 kg	0.5 × 3 m	06

NOTE: FY, Fiscal Year; USV, unmanned surface vehicle; UUV, unmanned underwater vehicle; RMS, Remote Minehunting System; SAHRV, semiautonomous hydrographic reconnaissance vehicle; LDUUV, long-distance unmanned undersea vehicle; BPAUV, battlespace planning autonomous underwater vehicle; TBD, to be determined; nmi, nautical miles; kt, knot.
SOURCE: Clifford Funnell (ed.). 2003. *Jane's Underwater Technology 2003-2004*. Sixth Edition. Jane's Information Group, Inc., Alexandria, Va., February.

Unmanned Surface Vehicles

Naval use of unmanned surface vehicles has a long history, beginning soon after World War II with deployments of remotely controlled target drones and mine sweepers. Recently, there has been enhanced interest in developing and using USVs for reconnaissance, surveillance, and mine-hunting missions in more nearly autonomous modes, as well as a continued use of the target drones.

To date, USVs have received neither the acceptance nor the attention in the Navy that has been given to other unmanned vehicles (unmanned ground vehicles (UGVs), unmanned aerial vehicles (UAVs), and UUVs). In particular, the Navy has no approved USV master plan. It appears that efforts regarding USV launch-and-recovery systems on surface platform hosts have limited emphasis. Among other things, hosts would prefer not to reduce speed or stop to either launch or recover USVs, because to do so might place the surface host platform at risk.

The number of USVs in existence or being developed is small compared with that of UGVs, UAVs, and UUVs. Three unmanned surface vehicles—the Spartan, Owl, and Roboski (detailed descriptions follow)—are mentioned frequently as candidates for naval use. The Remote Minehunting System (RMS), usually considered a UUV, is in fact a semisubmerged, air-breathing USV.

Most of the technology necessary for the development of USVs is mature and available. High-speed, low-observability, agile surface vehicles with acceptable endurance could be developed at reasonably low cost. However, various systems engineering aspects of these systems have not been adequately addressed, including how they will communicate with one another, with other unmanned vehicles, and with manned undersea, surface, and air systems; what sensor suites they might employ; and how they would best be launched and recovered.

Although current USV systems are used in a remotely controlled mode, opportunities for these systems, when used in an autonomous and adaptive control mode, are significant. For example, the increasingly hazardous mine-hunting process typically requires the acquisition of potential targets in order to identify, classify, and neutralize hazards. The cooperative action of multiple USVs with a broad range of sensing capabilities has the potential to improve mine-hunting capability significantly. Similarly, with multiple vehicles there is important potential for improvements in coverage rates for environmental and other survey missions if adaptive or intelligent autonomous control schemes become available.

USVs could also be effective in the areas of port and ship force protection. Current systems fulfilling these potentially hazardous roles are personnel-intensive. USVs appear to have promise for shallow water ASW and for countering swarms of small boats. USVs could also be assigned clandestine logistic roles to deliver and place seafloor sensors or seafloor energy sources for later use by UUVs, to shoot ground sensors ashore, to deploy seafloor or midwater acoustic arrays, or to place logistics packages in support of SEAL (sea, air, and land) teams or Special Operations Forces. Also, as discussed earlier, they could collect oceanographic data necessary to provide environmental information in support of warfighter systems and to detect the presence of chemical and biological agents.

Various naval USVs are described below:

- The autonomous search and hydrographic (ASH) vehicle and the Roboski were developed in the 1990s, initially as jet-ski type target drones for ship self-defense training. They are now also used as reconnaissance vehicle testbeds. They operate as remotely controlled vehicles and therefore are confined to line-of-sight operation.
- The Owl USV is a commercially available modification of ASH, with a low-profile hull for increased stealth and payload, operated as well in a remotely controlled mode. It has been used in demonstrations for marine reconnaissance in riverine and littoral situations. Today, several variants for stealthy USV sensor platforms have been proposed and are under consideration by the naval forces.
- The Spartan USV is an Advanced Concept Technology Demonstration (ACTD) started in May 2002. It is a modular concept, adapted to a 7-m-long rigid hull inflatable boat (RHIB) and fitted with various sensor and mission modules. It will be demonstrated in mine warfare, force protection, and precision strike sce-

narios, as well as for command and control of multiple USVs. This prototype system will have an endurance of up to 8 hours, a range of 150 nautical miles, transit speeds greater than 28 knots, and payloads of up to 2,600 lb. A larger version is contemplated based on an 11 m RHIB, with correspondingly larger payload and endurance.

- The Remote Minehunting System's mission is to detect, classify, localize, and identify bottom and moored mine threats in shallow and deep water. It is an air-breathing, diesel-powered semisubmersible that autonomously follows a preplanned mission plan. The vehicle deploys a variable depth sensor (VDS), comprising acoustic and EO sensors to positively identify objects as mines or nonmines. The VDS is the AN/AQS-20 airborne mine reconnaissance sensor, containing a suite of five acoustic sensors and the EO mine warfare sensor. The data link sends information collected by the VDS back to the host ship via line-of-sight or over-the-horizon transmissions. The first installations are planned for Aegis destroyers DDG 91 through DDG 96. System mission command, control, and display are incorporated into the AN/SQQ-89(V)15 undersea warfare combat system and operated by the host ship.

The RMS concept of employment starts with a launch of the remote, minehunting vehicle with its towed sensor package from the destroyer (DDG). The vehicle transits to the reconnaissance area prior to the DDG's entering the immediate area, and it conducts area reconnaissance by executing a preprogrammed mission profile. The processing onboard the RMS detects, classifies, and localizes minelike objects. Target imagery data and precise locations where data were gathered are radioed back to the DDG. The data are processed onboard the DDG to positively determine if the minelike object is indeed a mine. This process can be operator-initiated or automatic.

As mentioned above, this vehicle is large, almost 14,000 lb with the VDS, and is awkward to deploy or recover in any sea state above sea state 3. However, dedicated handling gear for deployment and recovery from the ship has been developed.

Unmanned Undersea Vehicles

Unmanned undersea vehicles are the most recent manifestations of a series of vehicles replacing divers to do work in the ocean. Manned undersea vehicles, usually called deep submergence vehicles (DSVs), were designed to go deeper than divers could. They were configured for ocean exploration, science, search, rescue, recovery, and survey.

To extend time on station at depth and remove risk to DSV occupants, remotely operated vehicles (ROVs) were introduced. A surface platform is required to launch, recover, and tend the ROV during operations. Control of the ROV from the surface is enabled through an umbilical link, which also supplies power. Telepresence (i.e., the use of television cameras on the ROV) permits observations from the ROV to be sent to the human controllers on the surface. In many circumstances, the high costs associated with the surface platform are justified, particularly when fine control, manipulation, or specific complex tasks are involved requiring human oversight. In other situations in which the task is routine and can be programmed, untethered systems, unmanned undersea vehicles, without need for umbilical links, that are either partially or totally autonomous, are an attractive alternative. Elimination of the umbilical link also reduces drag. Thus, untethered UUVs were developed for various offshore industry, science, and naval purposes, replacing many of the functions of towsleds and similar survey vehicles.

The opportunity to provide multiple simultaneous views by operating several untethered UUVs or using UUVs with a surface platform will greatly enhance their capabilities. For example, untethered UUVs are beginning to replace towed vehicles for seafloor survey, and they are enabling new kinds of inspections that were previously impossible (such as in New York City water tunnels); they perform surveys from shore, and improve the utilization of ship resources by operating UUVs simultaneously with other UUVs or other types of operations. However, as noted earlier, the intrinsic limitation of bandwidth for communications in the ocean requires much more substantial autonomy for an untethered system in the ocean than for a system on the surface or in the air.

The technology required for useful naval UUVs is mature and available. Available technology enables reasonable endurance, low observability, multimission capability, and modularity. The highest near-term naval payoff that will accrue to UUVs is likely to be in mine warfare, ASW, oceanography, and environmental reconnaissance. UUVs could also play roles as communications relays in conjunction with nuclear-powered submarines (SSNs) and manned or unmanned surface or air platforms, and in operations similar to those mentioned previously in this chapter for USVs.

The Navy-approved UUV Master Plan[2] provides a thorough and explicit roadmap for the continued development of UUVs, addressing their evolving capabilities, concept of operations, and technology and engineering issues. The UUV Master Plan cites numerous technical needs, including underwater communications, improved sensors, improved navigation, high energy density sources, and improved launch-and-recovery systems.

As noted earlier, there is an active, worldwide commercial interest in UUVs for the offshore oil, gas, and communications industries as well as active devel-

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[2]Program Executive Office for Undersea Warfare (PEO (USW)) and PMS-403 (Program Manager, Naval Sea Systems Command, for Unmanned Vehicles), Department of Defense. 2000. *The Navy Unmanned Undersea Vehicle (UUV) Master Plan,* U.S. Government Printing Office, Washington, D.C., April 20.

opments in the research community. These efforts need to be tracked and leveraged, where possible. The U.S. research community is supported in part by the Office of Naval Research, and the developments are well integrated into the Navy's vision for UUVs. Various naval UUVs are described below.

Semiautonomous Hydrographic Reconnaissance Vehicle System

PMS 325J Expeditionary Warfare developed the semiautonomous hydrographic reconnaissance vehicle (SAHRV) system, which is a modification of a system, called Remote Environmental Monitoring Unit System (REMUS), developed for routine autonomous surveys in coastal regions for the research community. This SAHRV system is widely used in the research community. It is human-portable (80 lb) and is equipped with sensors to measure conductivity, temperature, water depth, and optical backscatter. It has a side-scan sonar as well as an up-down-looking acoustic Doppler current profiler. Its modular design facilitates the installation of additional sensors, such as for bioluminescence. Navigation is provided using a short-baseline acoustic system. Control is exercised through a laptop computer that implements simple waypoint commands.

Planned improvements in the SAHRV system include computer-aided detection and classification, digital acoustic communications, upward-looking detection sonar, forward-looking obstacle-avoidance sonar, and precision navigation. In addition, an adaptive control system is under development that will allow dynamic reprogramming of a mission by an operator via acoustic communications or by threshold detection of onboard sensors. An adaptive control system allows the vehicle to follow a plume to its source or to determine regions of maximum concentration of bioluminescent organisms or pollutants. In addition, the capability for the vehicle to dock at a remote docking station, download the accumulated data, and recharge its batteries has been demonstrated.

PMS Explosive Ordnance Detachment is developing vehicles based on the REMUS platform to counter the threat of unexploded ordnance and reduce the threat to the Navy's teams. The detachment is also developing a vehicle to conduct mine reconnaissance in shallow waters (10 to 40 ft deep) close to hostile shores and is working to have an initial operating capability by mid-FY03 and full operational capability by FY05. Concurrent developmental efforts include vehicles to conduct harbor search and the clearance and reconnaissance of waters up to 300 ft deep and, leveraging the Joint Robotics Program, to develop ground crawlers to work in the surf zone. REMUS was used in Operation Iraqi Freedom by Special Forces, and it was used for explosive ordnance disposal in mine reconnaissance missions in the waterway and in the port of Umm Qasr.

Long-range Mine Reconnaissance System

The Long-range Mine Reconnaissance System (LMRS) is a UUV designed to be launched and recovered from a submerged submarine while it is under way at very low speed. The primary purpose of the LMRS is to extend the submarine's capability to conduct mine reconnaissance in clandestine fashion. The system is planned for the *Virginia*-class SSNs and nuclear-powered guided-missile submarines (SSGNs). LMRS launch requires a dedicated torpedo tube, and the recovery system occupies an additional torpedo tube, representing a considerable loss of flexibility for other kinds of submarine operations. The LMRS is a follow-on to the Near-Term Mine Reconnaissance System (NMRS), which was built to meet the specific needs of the submarine community to have a semiautonomous vehicle to perform reconnaissance ahead of the submarine. The NMRS was built using technology available in tethered torpedoes and sensors used by the mine countermeasures communities. The NMRS is tethered to communicate information back and forth, but the system is recoverable, unlike torpedoes. Four NMRSs were built and were deployed on selected submarines from 1998 to 2003. By meeting the specific needs of the Navy, the NMRS program can be considered a success.

One LMRS vehicle and a dedicated submarine launch-and-recovery system are in prototype development, with a planned IOC in FY05. It is apparent that the project is currently well behind schedule and over budget, to the extent that it has triggered an Office of the Secretary of Defense (OSD)-level review of whether to continue as originally planned. It is likely that an IOC in FY05 is not possible.

The technical problems of the LMRS in the areas of power and of navigation and launch and recovery are as follows. Given the 21 in. diameter of the vehicle, prescribed by the standard torpedo tube, the LMRS vehicle requires a great deal of power to provide sufficient speed for stability, as well as sufficient endurance to provide realistic standoff and surveying capability. The Navy has chosen to use high energy density, lithium thionyl chloride batteries, which have required an extensive and long process to be qualified for use in the vehicle's hull. While this may ultimately be a good solution for the energy, it has certainly created additional delays in the program. There are, in the committee's view, several technical deficiencies in this system, exclusive of the sensor package. The vehicle used an inertial navigation system, which may not achieve the level of accuracy required for the countermine mission; for such a mission, the objects being sought are of a scale smaller than the anticipated navigation error. Additionally, the launch-and-recovery system is cumbersome, requiring the attachment of an arm to the returning vehicle and then the insertion of the vehicle into the torpedo tube. This is a delicate process at best, when demonstrated by the mock-up system built on a floating dock—it is going to be problematic in real-world environments, especially given the limited stability and maneuverability of the LMRS vehicle at slow speeds.

As said above, this system, however flawed, needs to be used so that the Navy can begin to learn how to use a UUV for its ISR and countermine missions, and from this real-world experience develop appropriate CONOPS. If the OSD review triggered by the delays and budget growth results in a cancellation of the LMRS program, no experience will have been gained.

At present, the LMRS sensor package is similar to the package described above for the RMS (AN/AQS-20)—essentially the same variable-depth sensor suite used for airborne mine reconnaissance. Forward- and side-looking sonars are planned for IOC, and other sensors, such as synthetic aperture sonar (SAS) and improved acoustic communications systems (ACOMMS), will be added as they become available. These are currently scheduled to be added in FY06, to provide near-identification-quality imaging. The Precision Underwater Mapping System (PUMA) will be added in FY08, to increase the probability of detection of mines and to provide bathymetry capability as well.

The most significant limitation of the LMRS and the NMRS is their endurance, determined largely by the volume available for energy. In order to provide space for much larger payloads as well as the energy needed to support longer missions, a larger-diameter system is in conceptual development.

Multi-Reconfigurable Unmanned Undersea Vehicle

The multi-reconfigurable unmanned undersea vehicle (MRUUV) is the next step in the development of UUVs. It is intended as the follow-on to the LMRS. The MRUUV will include ISR sensors as well as ASW capabilities. In May 2003, the Navy awarded a $6.7 million design contract to Lockheed Martin for the MRUUV. Its design would have dimensions similar to those of a heavyweight torpedo—measuring 20 ft in length and 21 in. in diameter and weighing about 4,000 lb. The MRUUV will be able to reconfigure for different missions by switching modules. The modules will help the MRUUV perform the various missions, such as maritime reconnaissance, undersea search and survey, communications and navigation aid, and submarine trail and track. Lockheed's contract includes the development of a "mine identification" module. The MRUUV will be designed with an open architecture for technology spirals that enable less expensive upgrades to its system over the course of its service life. The IOC for the MRUUV is scheduled for FY07. The first platforms to receive the MRUUV will be *Los Angeles*-class and *Virginia*-class attack submarines.

Large Diameter Multi-Reconfigurable Unmanned Undersea Vehicle

The large diameter multi-reconfigurable UUV (LD MRUUV) is designed as a large bus, capable of being reconfigured to carry different sensor and mission packages. *Virginia*-class SSNs and SSGNs are the anticipated classes of host vehicles. Planned missions would include submarine track and trail, maritime reconnaissance (ISR), undersea search and survey, communications relay, navigation aid, and countermine activities. The diameter is as yet undetermined, but it is anticipated to be much larger than the standard 21 in. torpedo tube, which is the limitation for the LMRS.

LD MRUUV could carry and deploy several smaller, specialized UUVs into a contested area and serve as an energy recharging and data downloading docking station. It would extend the reach of the submarine into contested areas. This system could fulfill many of the roles imagined in the discussion of threats and potential naval operations, as discussed above, particularly ASW; littoral antisurface ship warfare; Special Operations Forces; clandestine intelligence, surveillance, reconnaissance, and targeting; and mine reconnaissance.

The projected IOC for the LD MRUUV is FY13. Technology requirements for this vehicle include a high-performance, renewable energy source, well-developed autonomy capabilities, and long-range, high-data-rate communications.

NAVAL OPERATIONAL NEEDS AND TECHNOLOGY ISSUES

The key naval operational needs and technical issues to be resolved in order to facilitate unmanned surface and undersea vehicles are delineated below. Some are common issues for both the USVs and UUVs:

- *Autonomous adaptive control systems, able to utilize sensor data in navigational and sensor control decisions.* This operational need requires extensive sensor fusion and onboard processing capabilities. Advances in adaptive autonomy are crucial for fulfillment of the needs discussed earlier.
- *Sensor packages to provide positive identification of mines and other objects of interest.* Meeting this need will require high-resolution, acoustic, and optical sensors whose prototypes are currently in development.
- *In-stride capability.* This requirement involves timely detection, identification, and neutralization of mines or other hazards in the sea-lanes of communications and supply, as well as in the littoral regions.
- *Launch-and-recovery systems for both USVs and UUVs a high priority.* This class of needs is most likely platform-specific, not "one size fits all," although the concepts may be generalized. Without safe and reliable recovery systems and adequate checkout and maintenance space, operations will be dangerous, critical learning in real-world environments will be prolonged, and the acceptance of unmanned vehicles in the fleet will be delayed. Of particular significance in this context is the need for the planning and development of launch-and-recovery systems for the Littoral Combat Ship.

A number of naval operational needs and technical issues specific to UUVs including the following:

- Energy storage, navigation, sensing, and control are probably the most significant technology needs for UUVs. Research and development in this area is extensive, particularly in the wireless industries, and their investment in these areas eclipses efforts of the DOD. As with other areas of intense industry interest, Navy UUV developers could leverage industry advances. This is especially important for energy storage, which is likely to continue to make the same kind of slow, steady progress as has been the case in the past. The continuing efforts at miniaturization and corresponding reductions in power-budget needs for sensors, computation, and the like will help alleviate the power needs of UUVs.
- The utility of autonomous vehicles is ultimately limited by the quality and quantity of the information that they have to guide them. To remain clandestine, both navigation and communication functions must work undersea with minimal exposure at the surface. High-performance inertial systems may provide suitable navigation for large vehicles, but will be prohibitive for small vehicles for which large numbers and expendability may be appropriate. The current high cost of inertial navigation systems may be alleviated in the future as the demand for these systems increases or as technological advances make them more affordable. For example, the Jet Propulsion Laboratory is developing a microelectromechanical system three-axis assembly that incorporates "tuning fork" gyro sensors and mixed-signal application-specific integrated circuits. These gyro electronics are designed to operate with approximately 12 off-ship components at a power draw of 75 megawatts.[3] Alternative technologies, integrated with low-cost inertial systems, may provide accurate UUV navigation in certain environments. Possibilities here might include low-frequency electromagnetic radiation in very shallow water or terrain-following methods.
- Since the ocean is relatively opaque to most electromagnetic radiation but transparent to acoustic radiation, virtually all long-range undersea sensing must be acoustic. However, optical sensing can be effective over short distances, on the order of meters, depending on water conditions. The continued miniaturization of acoustic and EO sensors and corresponding reductions in power requirements will make these sensor systems attractive for unmanned undersea systems. The reductions in size and power requirements, together with the expectation of significant onboard processing and fusion of raw sensor data, are extremely important in the context of the limited bandwidth of acoustic undersea communications, especially in shallow-water applications.

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[3]For additional information, see the Web site <http://nmp.jpl.nasa.gov/st6TECHNOLOGY/mems.html>. Last accessed on May 18, 2004.

One of the sensor systems that holds the greatest promise for mine warfare is the synthetic aperture sonar. This development appears to be on track and maturing. Once the SAS becomes available in the fleet, the hard work of developing expertise in interpreting the images will begin.

The Precision Underwater Mapping System—the principal integrated sensor package for LMRS and RMS, incorporating precision bottom bathymetry, side-scan and forward-looking sonar—is currently in development. This sensor package will be essential for realizing the capabilities of either LMRS or RMS and subsequent systems.

Navigation and communications are similar and interdependent in the underwater environment. If it is possible for the vehicle to come to the surface, then both GPS and RF or other communications channels are possible. Current methods for acoustic underwater communication in the open ocean are reliably working at rates of 2 to 3 kilobits per second (kbps) over 10 km. With large arrays and special circumstances, 10 kbps over 10 km is possible. To improve significantly on the current state requires the ability to predict and exploit special circumstances in the acoustic propagation characteristics. Improvements in this area will require a sustained effort in research focused on the next generation of acoustic propagation models, signal processing, and computational techniques. Underwater acoustics is an area of special interest and national responsibility for the Office of Naval Research, and one in which ONR has supported a vigorous and effective research effort. This effort needs to be sustained. Underwater acoustics will be the enabling technology for unmanned undersea vehicles.

In shallow water, the communications problem is even more complex and challenging because of the proximity of both the surface and the bottom reflections; this area of active research has met with some success. The rates of 2 kbps in this environment are only achievable under very special circumstances. If it is based on acoustics, the navigation problem is also challenging in the shallow-water environment, although there has been some promising work on using static magnetic fields in the very shallow environment in conjunction with the UGV crawler development. This is certainly an environment in which using GPS and RF communications at the surface may provide the most reliable navigation and communications link.

OPPORTUNITIES FOR IMPROVED OPERATIONS

The Navy has several systems in a prototype stage and in the acquisition process. These need to be used in the fleet so that lessons can be learned, as they have with the Predator and Global Hawk as well as with the smaller UAVs. These lessons and the inevitable and essential feedback to the system developers will both improve the systems and help bring about their acceptance in the naval community.

As discussed in many places in this and other chapters, the development of a robust, adaptive control system to provide reasonable autonomy and enable cooperation will be essential to realizing the opportunities for USVs and UUVs.

The Monterey Bay experiment—a component of the Autonomous Ocean Sampling Network, supported by ONR in the summer of 2003—was the first coordinated field experiment in which multiple UUVs were used in an adaptive observational program. They were used to determine the physical state and structure of a 50 km^3 volume of ocean. Multiple, dissimilar UUVs were operating in this volume to determine the temperature, salinity, and optical properties of the ocean water as they evolved over a period of 2 weeks. The vehicles and sensors were guided by the evolving output of a numerical model, which was assimilating the observations as the data were acquired.

The oil and gas exploration industry, along with the oceanographic research community, has led the development of small UUVs because it has required the technology, largely because of the high costs of ship time. Because of the focus on providing specific, focused technologies within limited budgets and time lines, these systems are available today and in wide use. The support for such developments comes from a broad range of sources in the research community, but ONR has played a key role in encouraging these developments. Continued leveraging of these assets and technologies will help in their acceptance and use within the naval forces. This has been the pathway to bringing the REMUS technology to the Special Operations community, which occurred largely through the efforts of ONR, and has led to the recent use of the SAHRV system in Iraq.

CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations based on the preceding discussions are presented in the following subsections.

Conclusions Concerning Unmanned Surface and Undersea Vehicles

Unmanned Surface Vehicle Roadmap

While the Navy's roadmap for unmanned undersea vehicle development is quite extensive and comprehensive, there is no similar planning document for unmanned surface vehicles. It is clear that the rather long history of development and even operational experience with UUVs facilitated the development of the UUV roadmap. Because USVs are much less mature, there is no similar experience base for them and hence the development of their roadmap will be more difficult. However, USVs can play increasing roles in the future, and a roadmap of their development is necessary.

Adaptive and Cooperative Autonomy

Improvements in the autonomous capabilities of USVs and UUVs are crucial to their future development. Of particular importance is the ability of these systems to adapt intelligently to changes in their tactical situations. As the missions of these vehicles evolve, it is inevitable that the tactical situation of specific missions will change, and their onboard sensing systems will indicate such changes. The onboard systems must be capable of recognizing the changes and adapting the mission plan accordingly, without the need for intervention by operators. Similarly, there is an increasing need for onboard autonomy that can facilitate the employment of multiple cooperative vehicles, both unmanned and manned.

Energy Storage for Unmanned Undersea Vehicles

The range and endurance of UUVs are directly dependent upon their onboard energy-storage capabilities. It is incumbent upon the Navy to keep cognizant of all commercial developments of energy-storage technologies and, in addition, to selectively fund the development of energy-storage technologies that are particularly applicable to UUV needs.

Launch and Recovery

Unless there are safe and effective systems for the launch and recovery of USVs and UUVs, these vehicles will not find their way into operations. In particular, there is an important need for launch-and-recovery systems for USVs while the mother ship is under way. Similarly, launch and recovery of UUVs, both at and below surface, are increasingly important.

Sensors for Mine Hunting

Mine hunting is possibly the most significant current mission for both UUVs and USVs. A sensor system to allow onboard recognition and classification of mines is an important technological need. In this context, the further development of synthetic aperture sonar technology is an associated need.

Underwater Communications

The need for high-bandwidth underwater communications for command and control of UUVs will be alleviated to some extent by increased autonomous capabilities of UUVs. However, further development of underwater communications methods for the transmission of sensed information and other needs is of paramount importance.

Logistics Needs of Autonomous Vehicles on the Littoral Combat Ship

While autonomous vehicles of all types are likely to be important contributors to the overall capabilities of the Littoral Combat Ship, there appears to be little or no planning for the maintenance and checkout space, launch-and-recovery equipment installation, and logistics support needs of these vehicles in the current development of the LCS. This planning needs to be accomplished.

Tracking Commercial Developments

The commercial-sector investment in technologies applicable to the missions of both USVs and UUVs dwarfs the investment that can be made by the Department of Defense. Hence, it is crucial for the Navy to be cognizant of commercial developments and to take maximum advantage of those developments insofar as they are relevant to the Navy's development of USVs and UUVs.

Environmental Sensing

The Navy has a long and distinguished history in the development and testing of methods for monitoring the sea environment. It is important for the future development of USVs and UUVs that this area of technology development be continued and strengthened in areas synergistic with USV and UUV developments.

Training

The complexity of complete UUV/USV systems, including the launch-and-recovery subsystems, demand well-planned and well-executed operations and maintenance training for those responsible for these systems.

Recommendations Concerning Unmanned Surface Vehicles and Unmanned Undersea Vehicles

Recommendation: The Navy and Marine Corps should aggressively exploit the considerable warfighting benefits offered by autonomous vehicles (AVs) by acquiring operational experience with current systems and using lessons learned from that experience to develop future AV technologies, operational requirements, and systems concepts. Specifically:

Accelerate the Introduction of Unmanned Undersea Vehicles. The Chief of Naval Operations (CNO) should direct the Commander, Fleet Forces Command, to deploy and evaluate systems such as the Long-Range Mine Reconnaissance

System, the Remote Minehunting System, and the Remote Environmental Monitoring Unit System in order to refine concepts of operations, cost issues, logistics, and handling.

Recommendation: The Assistant Secretary of the Navy for Research, Development, and Acquisition (ASN(RD&A)) and the Chief of Naval Research (CNR) should direct the Navy and Marine Corps Systems Commands, the Office of Naval Research (ONR), and the Marine Corps Warfighting Laboratory (MCWL) to partner with the operational community and monitor the concepts and development of critical autonomous vehicle-related technologies considered essential to the accomplishment of future naval missions. The progress of these developments should be tracked year to year. Specifically:

Pursue New Unmanned Surface Vehicle/Unmanned Undersea Vehicle Concepts and Technology Developments. The Chief of Naval Operations should establish a high-level working group to refine the requirements and concepts of operations for unmanned surface vehicles and other autonomous vehicles as an integral part of the Littoral Combat Ship (LCS) and other naval operations. Once the LCS design is completed, planning for logistical support, maintenance and handling space, and launch-and-recovery systems for autonomous vehicles should be incorporated.

The ASN(RD&A) and the CNR should direct the ONR to monitor commercial developments in unmanned surface vehicle (USV)/unmanned undersea vehicle (UUV) technologies and to take maximum advantage of those developments for meeting the Navy's needs. Specifically, the ASN(RD&A) and the CNR should direct ONR to invest in and develop networks of small UUVs. These efforts should include the leveraging of research and experimentation within the oceanographic research and oil exploration communities.

The ASN(RD&A) and the CNR should direct the ONR to conduct research into adaptive and cooperative autonomy and communications. ONR should develop better energy sources, as well as launch-and-recovery systems and environmental sensors for UUVs and USVs. Increased investment is needed in basic research and development in the areas of acoustics and optics as well as in sensors for mine hunting, including synthetic aperture sonar. ONR and the Naval Air Systems Command should focus on the modularity of components (propulsion, energy, and sensors), common architectures, common mission planning, and common integration pathways for data. The ASN(RD&A) and the CNR should ensure that UUVs and USVs, whenever possible, meet the interoperability and communications requirements of the Department of the Navy's FORCEnet operational concept.

6

Unmanned Ground Vehicles: Capabilities and Potential

INTRODUCTION

Unmanned ground vehicles (UGVs) have great potential for naval operations, playing an important role in support of Marine Corps combat; they can also assist in logistics operations ashore and afloat. The full development and deployment of UGVs capable of operating in a wide variety of situations require solving a number of difficult technical challenges.

Fortunately, the Navy and Marine Corps are not alone in developing UGVs, as the naval applications of UGVs overlap significantly with Army applications. In parallel with naval efforts, development programs sponsored by the Army, the Defense Advanced Research Projects Agency (DARPA), and the Office of the Secretary of Defense (OSD) have been ongoing for 20 years. At the system level, much progress has been made in road following; less progress has been made in off-road, cross-country navigation; and very little has been made in autonomous navigation through complex urban terrain. Some of the progress has been achieved through better understanding of the problems and through better algorithms; much of the headway may be attributable to faster computation.

Other government agencies are also developing UGVs or related technology: the National Aeronautics and Space Administration (NASA) uses UGVs for planetary exploration; the Department of Energy needs UGVs for nuclear site maintenance and coal mining; the Department of Homeland Security employs UGVs for search and rescue; and the Department of Transportation is developing UGVs as cars, trucks, and buses that can drive themselves or assist a human driver.

Commercial applications of UGVs are also beginning to be made—for example, in underground mining, strip mine haulage, crop harvesting, golf course mowing, ship cleaning, and for many other purposes. For logistics applications, a number of commercial automated guided vehicles (AGVs) are in daily use in factories around the world.

It is important that the Marine Corps and Navy leverage the efforts of other Services and industry. Several formal mechanisms exist to help with coordination. In 1990, the OSD established the Joint Robotics Program,[1] to coordinate all of the ground robot programs of the individual Services. The Department of Defense's (DOD's) UGV Master Plan[2] provides a comprehensive overview of the current programs and their status. The Joint Robotics Program works with the Unmanned Ground Vehicle Joint Program Office (UGV JPO) in Huntsville, Alabama; with the PMS EOD (Program Management Office for Explosive Ordnance Disposal in the Naval Sea Systems Command); with the Program Manager-Physical Security Equipment (PM-PSE); with the Air Force Research Laboratory; with the Army's Tank and Automotive Research, Development, and Engineering Center; and with technology base programs at DARPA, the Special Operations Command, and the Army Research Laboratory (ARL). The UGV JPO is a joint Army and Marine program. Significantly, the Future Combat System program, initiated by the Army and DARPA, is now a joint Army and Marine program also. The Marine Corps directly sponsors UGV development through the Marine Corps Warfighting Laboratory (MCWL). The Navy is active through the Naval Research Laboratory (NRL) and the Office of Naval Research (ONR). Navy laboratories have also played an important direct role in building robot vehicles: the Space and Naval Warfare Systems Command (SPAWAR), over the past two decades, has built a number of prototype UGVs both for naval applications and for other Services.

A recent study by the National Research Council[3] reviews UGV technology, applications, and programs in a U.S. Army context. The reader is referred to that report for a more complete treatment than appears here.

This chapter discusses the potential of UGVs for naval operations. It includes a description of the UGVs currently available or under development and a discussion of naval operational needs and technology issues and of opportunities for improved operations. It then presents the conclusions and recommendations of the committee with respect to UGVs.

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[1]For additional information, see the Web site <http://www.jointrobotics.com/>. Last accessed on March 31, 2004.

[2]For additional information, see the Web site <http://www.jointrobotics.com/activities_new/masterplan.shtml>. Last accessed on March 31, 2004.

[3]National Research Council. 2002. *Technology Development for Army Unmanned Ground Vehicles*, The National Academies Press, Washington, D.C.

THE POTENTIAL OF UNMANNED GROUND VEHICLES FOR NAVAL OPERATIONS

The Marine Corps can use unmanned ground vehicles (UGVs) in support of all phases of its operations ashore. They can be used to reconnoiter beach areas and landing zones prior to and during offensive operations, they can be used to explore "around the corner" or investigate interior spaces during urban operations, they can be used to investigate caves or other concealment areas in nonurban operations, and they can be used to provide physical security patrols for established or expedient command posts or bases in any hostile environment. UGVs can also carry weapons for use in any of the applications listed. Other naval applications include uses in base security, surf zone and beach mine clearing, explosive ordnance disposal at ranges, logistics (warehouse operations, ship lading, ammunition handling, supplies transport), and use as forward fire-control observation platforms for shore bombardment.

It is common to talk about autonomous vehicles, or robots in general, as being applicable in environments characterized by the three D's—dull, dangerous, and dirty. While that is certainly true, there are other words beginning with "D" that also make compelling cases for unmanned ground vehicles:

- *Diameter.* Unmanned vehicles can be built smaller or more strangely shaped than can a vehicle that must include a crew compartment. This latitude allows them to go places that a manned vehicle cannot go, to hide in smaller sites, and to be harder to see and to hit.
- *Difficult.* A small, manned vehicle bouncing over rough terrain gives images from its onboard camera that are very hard to follow. Teleoperation of such a vehicle is difficult, even for an experienced operator. Autonomous technology, doing computer-based visual surveying with onboard sensors and processors, can do a much better job of vehicle guidance.
- *Duration.* Autonomous vehicles can be capable of operating for much longer periods than a crewed system can. For a ground vehicle performing a mission such as overwatch (or artificial guards), the endurance can be measured in days or weeks instead of hours.
- *Digital.* Computer-controlled systems are inherently easier to integrate into the digital battlefield than human-controlled systems are: they accept commands in digital forms, they can have exact replicas of maps, and their reports come back as digital messages or digitized images.

The Navy (including ONR and SPAWAR) continues to be a leader in the research and development of robotic ground vehicles for naval as well as other Service and law enforcement applications. There is still a gap, however, between the research projects and the effective use of UGVs in real naval operational applications.

Unmanned Ground Vehicles and Unmanned Aerial Vehicles

The relative roles of unmanned ground vehicles and their airborne counterparts roughly correspond to the relative roles of Marines on the ground and Marines in the air. Unmanned aerial vehicles (UAVs) can travel long distances, have an excellent vantage for seeing large areas, and have easier lines of sight for communications. In many ways, aerial vehicles are easier to build, deploy, and control. Some jobs, however, must be done from the ground. UGVs have the potential to carry heavyweight payloads, to look inside buildings and under tree canopies, to persist for days, and to operate in all weather conditions. They also occupy ground: in some cases, the physical and visible presence of an armed unit on the ground is itself important. Thus, while the balance between air and ground forces is constantly being adjusted, the best approach for unmanned vehicles is to look at UGVs and UAVs as complementary parts of a team rather than as rivals for missions (and for funding).

In recent experiments sponsored by DARPA and by ARL, an unmanned helicopter and an unmanned ground vehicle demonstrated autonomous cooperation. In the experiments, the helicopter previews the ground vehicle's intended corridor of advance, building a three-dimensional model of the terrain. The ground vehicle then plans a detailed path, avoiding obstacles that the helicopter sees in the path of the ground vehicle. As the ground vehicle moves along the path, it compares its three-dimensional perceptions with the helicopter's three-dimensional map, registering the aerial and ground world models. The result is efficient travel, as well as a detailed map containing registered information from the vantage of both ground and air.

Overview of Current Military Unmanned Ground Vehicles

Unmanned ground vehicles can be described in terms of their size and functional utility. Included in this discussion are U.S. systems developed by or on behalf of all of the Services.

The heaviest class of UGVs is 15 tons and above. (See Table 6.1 for basic characteristics of these vehicles.) The fighting members of this class include automated or remotely controlled tank vehicles such as the Abrams Panther (over 40 tons); the D7G (a combat engineering vehicle) (28 tons); and the deployable universal combat earthmover (DEUCE) (18 tons). Each of these has the Standardized Robotics System (SRS) for teleoperation; the SRS provides a kit-based approach to converting standard vehicles to teleoperated mode. Also in this class is the automated ordnance excavator (AOE), a large (34 tons) armored excavator to be used for explosive ordnance disposal. All of these large vehicles are tracked. Of the four vehicles referred to here, only the Abrams Panther is deployed, with six Abrams Panthers operationally deployed in the Balkans and in the U.S. Cen-

TABLE 6.1 Heavy and Medium-Weight Unmanned Ground Vehicles Developed by or on Behalf of All of the Services

Name	Weight (tons)	Use	Traction	Status
Heavy				
Abrams Panther/SRS	More than 40	Mine clearance	Tracked	6 deployed
AOE	34	Explosive ordnance disposal	Tracked	Prototype
D7G/SRS	28	Mine clearance; excavation	Tracked	Prototype
DEUCE/SRS	18	Mine clearance; excavation	Tracked	Prototype
Medium				
T3 Dozer/SRS	9	Bulldozer	Tracked	Prototype
Smoke HMMWV	6	Obscuration	Wheeled	Prototype
ARTS-FP	4	Explosive disposal	Tracked	20 in use
DEMO III XUV	1.50	Experimentation	Wheeled	Prototype
Mini-Flail/Robotic Combat Support System	1.25	Mine clearance	Tracked	15 in use

NOTE: A list of acronyms is provided in Appendix D.

tral Command. The other over-15-ton UGVs are in development programs that have reached the prototype stage.

UGVs weighing between 1 ton and 15 tons are in the medium class. These vehicles include the All Purpose Remote Transport System (ARTS) (4 tons), which allows for multiple attachments or payloads for various combat-support activities; the mine-clearing Mini Flail (1.25 tons); and the eXperimental Unmanned Vehicle (XUV) (1.5 tons). (See Table 6.1 for basic characteristics of these UGVs.) All of the 1-ton-and-above UGVs in both the medium and heavy classes are automated or remotely controlled versions of manned vehicles except for the DEMO III XUV.

The next two classes (described in Table 6.2) are small (400 to 2,000 lb) and lightweight (less than 400 lb). These include vehicles designed from the start to be autonomous. Figure 6.1 shows these various UGVs by weight class.

Table 6.2 describes the small and lightweight UGVs that exist as prototypes or fielded systems. (Note that the weight is in pounds rather than tons.) The total number of fielded small and lightweight systems is 67 units of five types. The Dragon Runner and Gladiator are on track for future deployment. The Mobile Detection Assessment Response System (MDARS, both interior and exterior versions) is being developed to conduct security patrols and alarm response. Many of the other developmental efforts are dormant.

TABLE 6.2 Small and Lightweight Unmanned Ground Vehicles Developed by or on Behalf of All of the Services

Name	Weight (lb)	Use	Traction	Status
Small				
Gladiator	1,600	RSTA direct fire obstacle breaching	Tracked	Prototype
MDARS-E	1,500	Guard duty–exterior	Wheeled	SDD
MDARS-I	600	Guard duty–interior	Wheeled	SDD
RONS	600	Ordnance disposal	Wheeled	Fielded
Lightweight				
TALON	34 to 80	Multipurpose	Tracked	COTS
URBOT	65	Surveillance of small spaces	Tracked	2 deployed—SEALS
BUGS	45 to 60	UXO clearance	Tracked	Demonstration
Packbot	50	Multipurpose	Tracked	Fielded
ODIS	45	Undercarriage vehicle inspection	Wheeled	Demonstration
Matilda	40	Special operations, cave clearance	Tracked	24 in operational use
Dragon Runner	16	Situational awareness sentry or can be thrown	Wheeled	ACTD

NOTE: A list of acronyms is provided in Appendix D.

Status of Naval Unmanned Ground Vehicle Efforts

Some of the research and development programs on unmanned ground vehicles under way within the Navy and in the other Services and DARPA are described below.

Gladiator

The Gladiator tactical unmanned ground vehicle (shown in Figure 6.1) will be teleoperated or semiautonomous. This 1,600 lb UGV will operate in harsh, off-road environments. A prototype exists; the current program is expected to produce a fielded capability in 2006. The Gladiator will provide the Marine Air Ground Task Force (MAGTF) with a teleoperated/semiautonomous ground vehicle for carrying out combat tasks remotely in order to reduce risk and neutralize threats. The Gladiator is designed principally to support dismounted infantry during the performance of their mission, across the spectrum of conflict and the range of military operations. The primary functions of the Gladiator will be to provide the ground combat element with armed unmanned scouting and surveillance capabilities.

FIGURE 6.1 Examples of mission-specific unmanned systems, by weight class. NOTE: A list of acronyms is provided in Appendix D. SOURCE: Michael Toscano, Joint Robotics Program Coordinator, Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics (OUSD(AT&L)), Strategic and Tactical Systems (S&TS)/Land Warfare, "Autonomous Vehicles," presentation to the committee, December 10, 2002.

With the development of future mission payload modules (MPMs), projected operational capabilities may include reconnaissance, surveillance, and target acquisition (RSTA); engineer reconnaissance; obscurant delivery; direct fire (lethal and nonlethal); communications relay; tactical deception (electronic and acoustic); combat resupply; or countersniper employment. These modules will be field-installable, allowing commanders to increase their operational capability by tailoring the capabilities of the Gladiator to best meet their mission requirements.

Dragon Runner

The Dragon Runner (see Figure 6.2), at 16 lb (about 16 in. × 11 in. × 5 in.), can be tossed around a corner or through a window, for example. The wheeled vehicle can then be driven by remote control from an operator control unit (OCU) that displays imagery to the operator. The OCU is adapted from a Sony PlayStation, a system familiar to many of today's young Marines. In motion, the

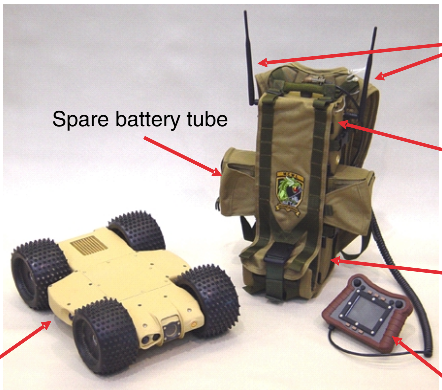

FIGURE 6.2 Dragon Runner system, including vehicle, operator control station (OCS), and backpack. SOURCE: Marine Corps Combat Development Command.

Dragon Runner will provide 6 hours of operation, and in a stationary "sentry" mode, 24 hours. The primary sensor is a low-light-level video camera. Dragon Runner is part of an ACTD program, with delivery scheduled in 2004.

Very Shallow Water/Surf Zone Mine Countermeasures

The Naval Sea Systems Command (NAVSEA) is conducting a Very Shallow Water/Surf Zone (VSW/SZ) Mine Countermeasures program for surf zone robotics. The goal is to develop a vehicle type that can be used to form teams for surf zone land-mine mapping and clearance. The concept is to use multiple vehicles to perform a coordinated search of a beach or surf zone area, send back imagery of suspected mines, document the location of each suspect object well enough to support reacquisition, and demonstrate the reacquisition, all in a timely fashion and robust against countermeasures. The required supporting technologies in the challenging surf zone environment are navigation, autonomous control of multiple vehicles, sensing—including detection, initial classification, and image capture—and communications. The "Very Shallow Water" part of the program introduces mine neutralization.

Status of Unmanned Ground Vehicles Developed by the Navy for Other Services

Mobile Detection Assessment Response System

The Mobile Detection Assessment Response System-Exterior (MDARS-E) is a joint Army–Navy development effort to provide an automated intrusion-detection and inventory-assessment capability for use at DOD storage sites. The program[4] is managed by the Office of Program Manager—Physical Security Equipment at Ft. Belvoir, Virginia. Overall technical direction for the program is provided by the Space and Naval Warfare Systems Center, San Diego. MDARS-E will patrol outdoor munitions and materiel storage sites. The onboard sensors support navigation (including obstacle avoidance), intruder detection, and inventory monitoring. The UGV patrols along a preprogrammed route defined by GPS coordinates. A system development and demonstration contract was awarded to General Dynamics Robotic Systems in January 2002, and an Initial Operational Test and Evaluation is scheduled to be conducted at Anniston Army Depot, Alabama, in FY06.

Man Portable Robotics System

The Army's Unmanned Ground Vehicles/Systems Joint Project Office (UGV/S JPO) is sponsoring the Man Portable Robotics System as an initiative[5] for the Joint Contingency Force Advanced Warfighter experiment. This tracked vehicle is intended to provide Special Forces with a means of reconnaissance in tunnels and sewers as well as other remote surveillance capability in urban warfare situations. Early experimental versions of this system were demonstrated in experiments conducted in 1999 and 2000. The system incorporates a digital telemetry link, which allows access by any Internet Protocol-based network.

Future Combat System

The Future Combat System (FCS) program is often described as a "system of systems." It includes innovations in ground force organization, communications, command and control, manned vehicles, munitions, and other areas. Most importantly for the purposes of this study, it also includes three unmanned ground vehicles: the armed robotic vehicle (ARV), the multifunction utility logistics

[4]For additional information, see the Web site <http://www.nosc.mil/robots/land/mdars/mdars.html>. Last accessed on March 31, 2004.

[5]For additional information, see the Web site <http://www.jointrobotics.com/history/program_his/2000.html>. Last accessed on April 1, 2004.

FIGURE 6.3 The Retarius vehicle from Lockheed Martin, featuring active articulated suspension. SOURCE: Defense Advanced Research Projects Agency.

equipment (MULE) vehicle, and the small human-packable ground vehicle. The ARV is to be a 6-ton scout vehicle, capable of long-distance, unrefueled travel over a wide variety of terrain. The MULE is smaller, approximately 2.5 tons, and is sized to carry rucksacks and to follow soldiers or marines cross-country. The small, human-packable UGV is designed to be carried in a rucksack by a single soldier for rapid deployment over short ranges. Each of these vehicles will have communications and command-and-control functions built in to connect with the larger FCS network system.

The FCS program began as a jointly managed DARPA/Army program. DARPA has sponsored the initial vehicle prototypes under its Unmanned Ground Combat Vehicle (UGCV) program, which includes the Retarius (Figure 6.3) from Lockheed Martin and the Spinner (Figure 6.4) from Carnegie Mellon.

Besides sponsoring the development of the vehicle hardware for the Perceptor (Perception for Offroad Robotics), DARPA also sponsored intelligent mobility software under its Perceptor program.[6] The Perceptor teams took standard Honda

[6]For additional information, see the Web site <http://www.darpa.mil/tto/programs/fcs_Per.html>. Last accessed on March 31, 2004.

FIGURE 6.4 The Spinner, from Carnegie Mellon University, with turbine power, electric final drives, and long-travel suspension. SOURCE: Available online at <http://www.darpa.mil/body/team_spinner.htm>. Last accessed on March 31, 2004.

all-terrain-vehicle platforms and added computer-controlled actuators, sensors, communication links, and power supplies to turn them into robot vehicles (Figure 6.5). The intent was to develop the vehicles under the UGCV program and the software under Perceptor, and then to use the knowledge gained from those two projects in the ongoing FCS program.

The other thread of robotic vehicle development is the ARL's Demo III/Collaborative Technology Alliances program. This program uses the XUV, a vehicle built by General Dynamics and specially designed to be a robotics testbed (Figure 6.6). The main emphasis of this program is tactically relevant mobility—which means driving over a variety of terrain and being supervised by soldiers over a moderate-bandwidth radio link. The Demo III vehicles have recently completed a series of tests covering more than 500 km, running in a combination of desert terrain, forest trails, and urban environments. This program continues in active development as part of the ARL Collaborative Technology Alliances program.[7] An important distinction between the Perceptor and Demo III is the

[7]For additional information, see the Web site <http://www.arl.mil/alliances/>. Last accessed on March 31, 2004.

FIGURE 6.5 National Robotics Engineering Consortium's Perceptor (Perception for Off-road Robotics) vehicle. SOURCE: National Robotics Engineering Consortium, Carnegie Mellon University. See the Web site <http://www.rec.ri.cmu.edu/projects/perceptor/perceptor.shtml>. Last accessed on March 31, 2004.

amount of a priori data available to the vehicle to facilitate navigation. Perceptor tests were on unrehearsed terrain (i.e., the team had no a priori knowledge of the terrain, whereas many of the Demo III tests were rehearsed over familiar terrain). This difference highlights the difficulty in comparing performance and emphasizes the need for comprehensive metrics.

NAVAL OPERATIONAL NEEDS AND TECHNOLOGY ISSUES

Operational Needs

The most significant naval operational need that can be addressed by UGVs is that of mine detection and clearance in the surf zone and beach area in support of amphibious operations. Surf zone mines threaten landing craft, and antipersonnel

FIGURE 6.6 The General Dynamics experimental unmanned vehicle (XUV). SOURCE: National Institute of Standards and Technology; see the Web site <http://www.isd.cme.nist.gov/documents/hong/SPIERoad_Detect.pdf>. Last accessed on March 31, 2004.

mines inland endanger and impede the advance of the landing force. Current approaches to detecting and clearing these mines are either inadequate or slow and expensive. For example, Bangalore Torpedoes or snake charges work to clear the antipersonnel mines, but they are heavy and impose a large logistics burden. Remote-sensing techniques are not up to the job, especially when there is vegetative cover. Surf zone mines, intended to destroy landing craft, can be dealt with by SEAL (sea, air, and land) teams (sometimes aided by aquatic mammals), but this is a dangerous, time-consuming, and expensive process. The VSW/SZ Mine Countermeasures program as described earlier is working to address these issues using UGVs, but the results of that program are not mature enough for deployment.

Many other applications of UGVs in support of Navy and Marine Corps operations are possible; they overlap with Army or civilian applications. These applications are briefly outlined in the section above entitled "The Potential of

Unmanned Ground Vehicles for Naval Operations," and they are detailed in the 2002 report of the National Research Council on Army UGVs.[8]

Unmanned Ground Vehicle Technology Issues

While unmanned ground vehicles share many technical challenges with unmanned aerial vehicles and unmanned undersea vehicles, several unique aspects of UGVs have influenced and limited their development. The most obvious is the complexity of the operating environment. Ground vehicles operate in a cluttered and unpredictable environment containing obstacles that are not known at any detailed level before the mission. Thus, as discussed below, the basic problem of planning and executing a route from point A to point B is one of the fundamental tasks still being researched.

Basic Mobility Issues

Sensors. Very little sensor development has been specifically driven by the needs of ground robots. Military sensors are typically developed for long-range target detection. The resulting sensors typically are large (e.g., 8 in. optics) and heavy and have a very narrow field of view. Sensors for local navigation, in contrast, must be small enough and light enough to be mounted on a small robot bouncing over rough terrain, and they must have a wide or adjustable field of view in order to see objects in the path of the vehicle. Typical mobile robot sensors include video and infrared (IR) imagers, stereo video systems, scanning laser rangefinders, millimeter radars, and ultrasound. Trade-offs between these sensors include active versus passive sensing, limited capability versus all-weather day-or-night operation, required range and resolution, and required recognition capabilities.

Sensor Interpretation. Raw sensor data (such as images and range measurements) need to be interpreted by computer algorithms in order for useful information to be generated. It is fairly straightforward to measure distances and sizes: stereo or LIDAR (light detection and ranging) or radar processing can yield the range of an obstacle, the roughness of the terrain, or the size of a rock. It is much more difficult to automatically label the data: is an object a soft bush or a hard rock, a hard surface or quicksand, a fixed obstacle or a mine or an unpredictable pedestrian? Some of those decisions can be made reliably with current technology, but others are beyond the state of the art. More difficult yet is generating inferences—a person acting in

[8]National Research Council. 2002. *Technology Development for Army Unmanned Ground Vehicles,* The National Academies Press, Washington, D.C.

such and such a way is likely to be hostile, or a ball bouncing across a road may indicate that a child will chase it into the roadway.

Planning. Geometric planning is fairly well understood. It is straightforward to plan a route that optimizes a combination of good traversibility, stealthy motion, and minimal travel time. It is also straightforward to update that route on the fly, as new information is perceived and added to the map. It is far more difficult to automatically plan and execute maneuvers that include multiple cooperating vehicles in combination with unknown terrain and unknown threat conditions and to assess those threat conditions.

Behaviors. At the lowest level of robot driving, the fastest loops of the control system are referred to as "behaviors" instead of "deliberative plans." Typical robot behaviors include reflexive obstacle avoidance, road following, formation keeping, or steering to avoid tipping over on steep-sided slopes. Building individual behaviors is often possible; combining multiple behaviors into a coherent system is still not completely understood but needs to be accomplished.

System Architecture. To combine sensing, sensor interpretation, planning, plan execution, behaviors, and user interactions requires a systems architecture. Mobile robots have several different approaches to systems architectures, depending on the complexity of the various components. The "best" systems architecture for mobile robots has not yet been identified.

User Interface. Even in the best of cases, teleoperation (remote control) of a ground vehicle is not easy. The optimal conditions for a remote operator include good video sensors on the robot that are properly positioned to see the edge of the vehicle as well as the surrounding terrain, high-bandwidth links (fiber optic or radio) with appropriate latencies to the remote control station, wide-screen displays, an "artificial horizon" indicator similar to those on aircraft, anomaly detection, and a comfortable layout of controls. Despite all these user conveniences, teleoperators can become disoriented, lose track of obstacles behind the vehicle, and fail to notice gradually increasing side slopes leading to vehicle rollover, and they often become nauseous when the bouncing video from a rough-terrain vehicle does not match the cues from their own inner ears. These difficulties are exacerbated by poorer-quality sensors on the vehicle, lower-bandwidth communications links, smaller or dimmer displays, and by operators being under pressure from fatigue or enemy fire.

Research continues to improve the situation, through telesupervision (higher-level control, such as designating waypoints); better interfaces (wearable displays); and multimodal interfaces (robots that can follow voice commands or hand signals). The most sophisticated interfaces use a combination of levels of command, so the user can either work at a low level for tight vehicle maneuvers or can give the robot higher-level tasks and then focus user attention on other activities until the robot reports success or asks for additional directions.

Communications, Power, and Mechanism Design. Besides all of the robot-specific issues mentioned above, unmanned ground vehicles need all the other components of any vehicle system. Communications can be by tether cable, line-of-sight radio, multihop links, or low-bandwidth, non-line-of-sight radio. For some environments (e.g., caves) or some missions (reconnaissance), complete radio silence may be enforced by physics or by doctrine. Power supplies for a large robot vehicle are not difficult—diesel engines or turbines provide good power sources, with battery backup. But for smaller robots, power supplies become a major limiter of speed and range. Similarly, mechanism design for a UGV can take advantage of military vehicle designs, including those for tracks, wheels, and hovercraft. Specialty vehicles have been built with legs (eight or six for stable walking; four, two, or even one for running and hopping) and hybrid designs (e.g., wheels on the ends of legs).

Mission Payload Issues

Beyond the problems of basic mobility, a UGV must perform a useful mission. Mission payloads involve another set of issues: target detection and tracking for a reconnaissance vehicle, cargo lifting and hauling for a logistics vehicle, path tracking and safe intervehicle separation for automated convoys, and so on. Each of these areas is partially understood and continues to be the topic of ongoing research and development.

Surf Zone Unmanned Ground Vehicles

The UGV technology need specific to unmet naval needs is surf zone mobility. This is a challenging environment for an autonomous vehicle that is attempting to conduct a complete survey of its assigned beach area. The many difficult technical problems in mine hunting in very shallow water include these:

- *Mobility.* Wave action, soft soil, and rough terrain all impede motion.
- *Perception.* In shallow water or the surf zone, the water is often turbid, making video sensing difficult. Acoustic sensing is also limited by reflections from the surface and bottom and by acoustic noise from breaking waves.
- *Communications.* Acoustic communications are typically limited to low bandwidths or short ranges, due to the same factors that limit acoustic sensing. Radio communications are only possible if the provisional antenna remains clear of the water surface.

- *Power.* Air-breathing power systems using a snorkel are difficult to implement in the surf zone. Battery power is the most practical approach, but that limits the range and endurance of the vehicles.

Since the beginning of the 1980s, a series of research and development programs has addressed the issues listed above, first through the DARPA Lemmings program (by Arnie Mangolds at Foster-Miller) and then through the ONR VSW/SZ Mine Countermeasures program. The current state of the art uses the SeaTALON (a multimission detection and tracking system for littoral battlespace) platform, based on the Foster-Miller Talon land-based vehicle, which is in active military Service. The TALON is a straightforward vehicle with two nonarticulated tracks; the vehicle is 34 in. × 22.5 in. × 11 in. in its stowed condition. Work on the crawler platforms and the VSW/SZ countermine mission is in current progress on two main fronts—the SeaTALON platform and the associated sonar system are being implemented (Figure 6.7) and thoroughly tested in a progression of field tests and exercises, and the needed countermine sensors and imagers are being developed and put into configurations suitable for installation on the SeaTALON and use by the fleet.

Current instrumentation on the SeaTALON includes a suite of sensors—low-light, gray-scale video cameras; specialized illumination sources for underwater viewing; a scanning laser; and a rotating sonar head (Figure 6.8). Nonimaging sensors under development include tactile sensors to feel mines, chemical sensors to sniff mine residue in the water column, and magnetic mine sensors. Typical communications systems either send compressed images directly over acoustic links or use a radio utility float that can transmit real-time video.

There are alternative systems approaches to the problem of antipersonnel mines impeding dismounted advance ashore. Note that the use of Bangalore Torpedo line charges is very effective in clearing a path; however, the weight of the devices and the slowness of employing them make them logistically undesirable, because they have to be carried and manually handled in the landing operation. But a UGV could be designed to walk ahead of the advancing column: it could lay out the line charge ahead of itself and detonate the charge so as to semiautonomously (it could be steered by a member of the column advancing behind it) clear a safe path to the objective cover behind the beach landing zone. Alternatively, a UGV similar to the Mini-Flail could lead advancing troops. Note that the Mini-Flail has experienced difficulties with barbed wire entanglement; the line charge approach does not have that problem.

The technology programs in support of UGV systems are “bottom-up” programs. That is, they are driven more by technological capability than by top-down consideration of unmet mission needs. The alternative approaches to surf zone mine clearing described above result from a top-down consideration of the mission need. The Navy (and Marine Corps) need a small group whose function

FIGURE 6.7 Two SeaTALONs in a surf exercise. SOURCE: Department of the Navy.

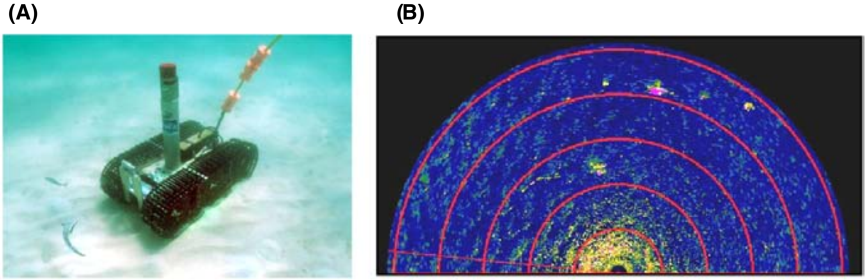

FIGURE 6.8 (A) Rotating-head sonar mounted on a tactical autonomous robot (TAR) crawler during reacquisition exercises. (B) An example of a half-field scan; range lines are 10 m per division; five targets are visible in the scan. SOURCE: Department of the Navy.

is to investigate the possible fulfillment of unmet needs by UGVs (or indeed by any autonomous platform). The group needs to work toward the synthesis of systems that fulfill unmet mission needs in ways other than automating the operational procedures currently used by manned systems.

OPPORTUNITIES FOR IMPROVED NAVAL OPERATIONS

The main integration issue for improved naval UGV operations arises with the conduct and the products of reconnaissance, surveillance, and target acquisition (RSTA) activities. The use of UGVs in motion or "perching" ashore offers promise of an effective and inexpensive monitoring capability in support of shore bombardment and pre-invasion preparation of the battlefield. In order to reap the full benefit, the imagery needs to be formatted and indexed compatibly with RSTA products available from other Navy and other Service systems. Thus, UGVs with RSTA capability could use Internet Protocol packets for communication (to participate in the Global Information Grid (GIG)) and could use GPS coordinates for positioning information when possible. (In certain situations GPS is not available to a UGV—for example, in tunnels, caves, some urban environments, or in a jamming environment.)

One of the goals of increasing the autonomy of UGVs is to decrease the operational demand on Marines in the field. The current mode of controlling UGVs locally creates a burden and a distraction for the operator. For long-range scouting missions, the control of UGV systems could be accomplished from onboard ship or from a secure facility. If significant advances in autonomy can be accomplished, the control could be integrated into the command-and-control system used for UAVs. On the other hand, in the case of UGVs used in close cooperation with ground forces such as for mine clearance to support advance from a beachhead, it will be essential that the control of the UGVs be possible from the forward-deployed units at a low echelon of command. This arrangement will facilitate flexible response as the tactical situation unfolds in the field.

The advancement of UGVs is dependent on a wide variety of technologies that have matured to very different levels. Manipulators, arms, sensors, and basic mobility have been critical to commercial robotics for several decades and are well developed for controlled environments. Perception, planning, and navigation in cluttered and unpredictable environments are much less developed. In order to make useful progress, it is essential to focus on the system as a whole, beginning with a clear mission need and taking into account during the development of vehicles the entire range of considerations in the use of the vehicle. Such considerations include the following:

- How will the system be tested and validated?
- How will the vehicle be transported to the battlefield?

- Where will it be stored until it is used?
- How will it be fueled and maintained?
- How will it be deployed from its storage?
- Where will it be controlled/monitored from?
- How will it communicate?
- How will it handle unexpected situations?
- How will it be retrieved after it is employed?
- How will the users be trained?
- How will the vehicle be integrated into command-and-control structures?

These are just some of the questions to be considered, but it is important that a major component of the research and development efforts be aimed at these types of practical considerations, framed by a clearly defined mission task description.

One way to focus research on these types of issues is to develop real-world challenges and competitions that encourage researchers to focus on accomplishing a mission in a real-world environment with a view of the systems requirements. Allowing developers to compare the capabilities of their machines would provide regular benchmarks of the state of the art. Such competitions might be sponsored by professional societies or DOD entities, but they could be encouraged by Navy participation, as appropriate, and by encouraging Navy-supported researchers and developers to compete.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions and recommendations based on the preceding discussions are presented in the following subsections.

Conclusions Concerning Unmanned Ground Vehicles

Leveraging Efforts of Other Services

The Navy has a well-established position in the research and development of unmanned ground vehicles. Although certain specific needs are unique to the Navy mission, it is important that the Navy and Marine Corps leverage the efforts of other Services as well. Several formal mechanisms exist to help with this coordination, including the Office of the Secretary of Defense Joint Robotics Program.[9] Programs of particular significance for collaboration are the Unmanned Ground Vehicle Joint Program Office; work at the Air Force Research Laboratory; the Army's Tank and Automotive Research, Development, and Engineering Center; and tech-

[9]For additional information, see the Web site <http://www.jointrobotics.com/>. Last accessed on April 1, 2004.

nology base programs at the Defense Advanced Research Projects Agency, Special Operations Command, and Army Research Laboratory.

Mine Detection and Clearance in the Surf Zone

Mine detection and clearance in the surf zone and beach area constitute the most significant naval need that can be addressed by UGVs. Bangalore Torpedoes or line charges work to clear antipersonnel mines, but they are heavy and impose a large logistics burden. Remote-sensing techniques provide a partial solution but are inadequate in the surf zone and on land areas with vegetative cover. SEAL teams (sometimes aided by aquatic mammals) are very effective, but mine detection and clearance in surf zones and beach areas are dangerous, time-consuming processes. The Very Shallow Water/Surf Zone Mine Countermeasures program is working to address these issues.

Surf Zone Technology Needs

The surf zone is an extremely challenging environment for autonomous vehicles. Particular issues in this environment are mobility, perception, communications, and energy storage. Since the surf zone is rather unique to the Navy mission, the technology needs for UGVs operating in the surf zone are not likely to be addressed by the other Services or the commercial sector.

Sensors and Sensor Data Interpretation

There is a strong need for advanced sensing systems for UGVs. Very little sensor development has been specifically driven by the needs of ground robots. Thus, many sensors that would be useful on UGVs are large and heavy and have a very narrow field of view. Sensors for local UGV navigation, in contrast, must be small enough and light enough to be mounted on a small robot bouncing over rough terrain, and they must have a wide or adjustable field of view for seeing objects in the path of the vehicle. The perception subsystem of a UGV takes the data from sensors and develops a representation of the world around the UGV, called a world map, sufficient for taking those actions necessary for the UGV to achieve its goals. Without the perception capability, there can be no fully autonomous operation, and without a high level of autonomy the transformational potential of UGVs will not be realized.

Raw sensor data (e.g., images and range measurements) need to be interpreted by computer algorithms in order to generate useful information. In particular, the ability to automatically distinguish, for example, between a soft bush and a hard rock, a hard surface and quicksand, a fixed obstacle and an unpredictable pedestrian, is important for path planning of USVs.

Planning and Behaviors

The onboard automated planning of vehicle actions is a fairly mature technology at present, but there are significant needs in this area as well. It is straightforward to plan an appropriate route using a stored map and to update that route as new information is received and added to the map. It is more difficult to automatically plan and execute maneuvers that include multiple cooperating vehicles in the presence of unknown terrain and unknown threat conditions.

At the lowest level of robot driving, the fastest loops of the control system are referred to as "behaviors" instead of "deliberative plans." Typical robot behaviors include reflexive obstacle avoidance, road following, formation keeping, or steering to avoid tipping over on steep-sided slopes. Building individual behaviors is often possible with current technology, but how to combine multiple behaviors into a coherent system is still not well understood.

User Interfaces

The remote operation of UGVs is a continuing area of difficulty. Teleoperation of a ground vehicle is usually difficult in many operational environments, as operators become disoriented, lose track of obstacles that may be behind the vehicle, fail to notice gradually increasing side slopes leading to vehicle rollover, and often become nauseous when the bouncing video from a rough-terrain vehicle does not match the cues from their own inner ears. There is an important need for effective human interfaces to facilitate the teleoperation of UGVs or to extend true autonomous capability.

Recommendations Concerning Unmanned Ground Vehicles

Recommendation: The Navy and Marine Corps should aggressively exploit the considerable warfighting benefits offered by autonomous vehicles (AVs) by acquiring operational experience with current systems and using lessons learned from that experience to develop future AV technologies, operational requirements, and systems concepts. Specifically:

Accelerate the Introduction of Unmanned Ground Vehicles. The Office of Naval Research should support continued research into the use of unmanned ground vehicles (UGVs) as a potential solution to the mapping and clearance of surf zone and beach mines, and into UGV alternatives to unmanned aerial vehicles for surveillance missions in support of shore bombardment. Testing and development of the Gladiator and Dragon Runner should be increased in order to refine the capabilities of both systems. Partnering by the Navy and Marine Corps with the U.S. Army's Future Combat System program in research and development efforts to develop UGV components should be encouraged by the Navy and Marine Corps.

Recommendation: The Assistant Secretary of the Navy for Research, Development, and Acquisition and the Chief of Naval Research should direct the Navy and Marine Corps Systems Commands, the Office of Naval Research (ONR), and the Marine Corps Warfighting Laboratory (MCWL) to partner with the operational community and monitor the concepts and development of critical autonomous vehicle-related technologies considered essential to the accomplishment of future naval missions. The progress of these developments should be tracked year to year. Specifically:

Pursue New Concepts and Technology Developments for Unmanned Ground Vehicles. The ONR should pursue a broad spectrum of research and development (R&D) on unmanned ground vehicles themselves and on their components. The R&D should range from basic research in sensors and sensor processing to field tests of complete systems. The Navy should continue to partner with the Office of the Secretary of Defense, the Defense Advanced Research Projects Agency, and the Army, as appropriate, utilizing the capabilities of the Space and Naval Warfare Systems Command for these activities.

7

Integrating Autonomy in Network-Centric Operations

Previous chapters in this report focused on unmanned aerial, surface, undersea, and ground vehicles and on the operational requirements associated with them. This chapter discusses areas such as the command, control, communications, intelligence, surveillance, and reconnaissance (C3ISR) that are critical for integrating unmanned aerial vehicles (UAVs) into network-centric operations. Many knowledgeable observers, including this committee, believe that communications-capacity limitations, interoperability problems, and imagery-processing and -exploitation issues head the list of impediments to a more rapid introduction and utilization of UAV systems by the military in general and the Navy in particular. Although this chapter is focused on C3ISR for UAVs, Chapters 5 and 6 contain some discussion of command and control (C2) for unmanned undersea vehicles (UUVs), unmanned surface vehicles (USVs), and unmanned ground vehicles (UGVs); sensors; and communications.

UNMANNED AERIAL VEHICLE COMMAND AND CONTROL

Current Systems

Command and control of UAVs is currently accomplished using proprietary systems developed by their manufacturers. For example, the Predator C2 system (Figure 7.1) incorporates hardware and software for manually making the aircraft take off and land. The aircraft can automatically fly between planned waypoints, or it can be flown manually. Aiming the imaging payload is done manually, as is designating a target with the laser designator. The Predator ground component

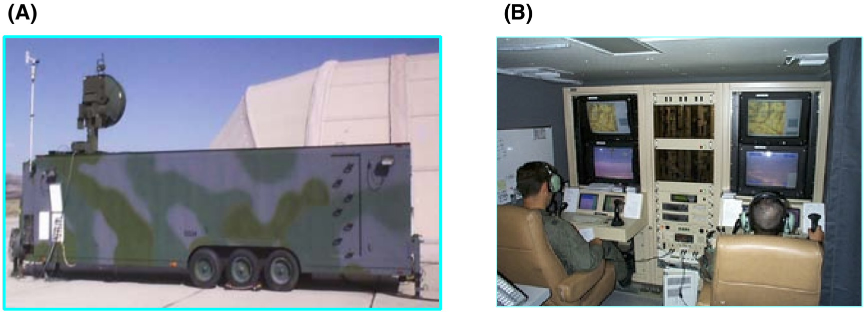

FIGURE 7.1 (A) Predator ground station. (B) Operator stations. SOURCE: Maj David Gibson, USAF, Director of Surveillance and Reconnaissance, Headquarters, U.S. Air Force, "Predator in Support of the Global War on Terrorism," presentation to the committee, February 25, 2003.

normally fills one militarized semitrailer (Figure 7.1A), although more austere ground systems are available.

The Global Hawk provides a hands-off, fire-and-forget mode of operation by preplanning and scheduling not only routes but locations to be imaged. With one keystroke the Global Hawk will taxi to the runway, take off, perform its mission, and return and land accurately without further human intervention. The "pilot's" main responsibility is receiving and returning messages from air traffic control and monitoring telemetered aircraft status data. The control segment for takeoff and landing, the launch-and-recovery element (LRE), is built into a short, enclosed semitrailer, and the mission-monitoring component, the mission control element (MCE), is built into a militarized semitrailer.

The Dragon Eye, as a human-portable system, has its command-and-control system integrated onto a laptop computer (Figure 7.2).

Tactical Control System

As indicated above, current UAV command-and-control systems are proprietary to the UAV manufacturer, and they lack interoperability in the sense that it is not possible to control one UAV using the C2 system of another. To address this problem, the Navy has been developing the Tactical Control System (TCS) in order to provide a single product for the control of UAVs from the different manufacturers. TCS has an open architecture that includes software generic to all UAVs, and it provides the capability to integrate software peculiar to a particular UAV.

Although TCS has been adopted as the standard Navy product for UAV command and control, and it has been influential in the ongoing development of

Features –

- Waypoints plotted on a moving map
- In-flight re-tasking capability
- Operates Defense Mapping Agency products
- Maps automatically geo-register with GPS
- Any National Imagery and Mapping Agency (NIMA) products can be loaded
- Digital Terrain Elevation Data (DTED) used in mission planning
- Maps downloaded from NIMA Web site

Panasonic Toughbook 34

FIGURE 7.2 Dragon Eye command and control. SOURCE: Col Barry Ford, USMC, Chief of Staff, Marine Corps Warfighting Laboratory, "Autonomous Vehicles in Support of Marine Corps Operations," presentation to the committee, December 9, 2002.

standards for UAV interoperability (e.g., STANAG 4586 (Standard Interface of the Unmanned Control System (UCS) for NATO UAV Interoperability)), it has in practice not been widely adopted by UAV manufacturers and other Services. This is partly due to organizational issues and lack of incentives, but there are practical issues as well. Since a ground control station is required in the development and testing of a UAV, it is a natural by-product of this process. Thus, TCS has to play "catch up" (by developing or integrating software peculiar to the UAV) with the ground station already developed by the UAV manufacturer after the UAV development process is complete.

This may be a sign of relative immaturity for UAV programs—or a sign that the Department of Defense (DOD) and the Department of the Navy have not yet coordinated development requirements. In any event, there is room for progress here.

Mission Command and Control for Uninhabited Combat Air Vehicles

With the exception of the MQ-1 Predator with the Hellfire missile, current UAVs have had intelligence, surveillance, and reconnaissance (ISR) missions, not combat missions. The development of the uninhabited combat air vehicle (UCAV) will dramatically change this situation. Figure 2.2 in Chapter 2 depicts a concept of operations (CONOPS) for a UCAV suppression of enemy air defense (SEAD) mission. Three UCAVS are cooperating to detect air defense radars using time difference of arrival (TDOA) and frequency difference of arrival (FDOA) techniques. Then two pairs of UCAVs, cued by the TDOA- and FDOA-derived estimates of target location, cooperate to destroy these radars. One UCAV of each pair uses its synthetic aperture radar (SAR) to geolocate the target based on the cue it has been provided, while the second UCAV delivers a weapon based on the target position data provided by the first UCAV. The first UCAV then uses its SAR to perform battle damage assessment to see if restrike is necessary. Note that tight coordination and timing of actions by the different air vehicles is required, thereby imposing stressing requirements on C2. The presence of manned as well as unmanned air vehicles in the air space will only increase the difficulty of satisfying these requirements.

To efficiently and effectively perform its mission, the UCAV system will require an advanced command-and-control system. Indeed, the Defense Advanced Research Projects Agency (DARPA) and the Services have established research and development (R&D) programs to develop the needed mission control technology.

Conclusions Concerning Unmanned Aerial Vehicle Command and Control

The Navy needs to evolve the Tactical Control System from a focus on providing a single-product solution for UAV command and control to a program providing the technological basis and proof of concept for Navy leadership in an effort defining standards and protocols for UAV control. The long-term objective would be to permit a UAV of any Service and manufacturer to be controlled using a ground station of any other Service and manufacturer. This effort could be conducted in coordination with the ongoing efforts of the Office of the Secretary of Defense.

To cope with the increasing complexity of UAV missions as exemplified by the Joint Unmanned Combat Air System (J-UCAS) and to take full advantage of the potential for reduced numbers of personnel required, the Navy needs an aggressive research program in intelligent autonomy. This research program may be focused on the development of automation aids to allow tightly coordinated control of multiple UAVs by a single operator, including automated real-time mission planning and replanning. This effort could be conducted in coordination with the efforts of DARPA and the Air Force.

UNMANNED AERIAL VEHICLE COMMUNICATIONS

Current Communications Systems

Unmanned aerial vehicle communications systems are used to uplink (from ground segment to vehicle) C2 data and to downlink (from vehicle to ground segment) C2 and sensor data. Although C2 data are of relatively low rate (typically in the range of a few hundred kilobits per second [kbps]), sensor data dissemination requirements are much higher and stress available link capacities.

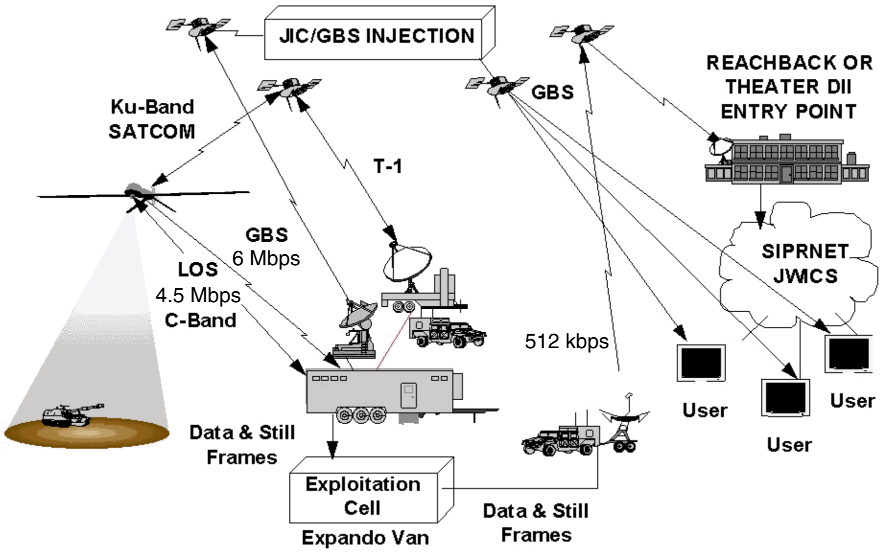

FIGURE 7.3 Predator communications architecture. NOTE: A list of acronyms is presented in Appendix D. SOURCE: Maj Scott Hatfield, USAF, USAF Command, Control, Intelligence, Surveillance, and Reconnaissance Center, "Predator Support to NATO Operations," briefing to Unmanned Aerial Vehicle Conference, September 21-23, 1999.

Particular dissemination throughput requirements are a function of sensor type, ground track resolution, data compression, and any onboard processing. Figures 7.3, 7.4, and 7.5 illustrate the communications architectures for the Predator and Global Hawk UAVs. These architectures rely both on line-of-sight (LOS) communications and on military and commercial SATCOM (satellite communications) over-the-horizon (OTH) communications. Like UAV C2 systems, UAV communications systems are primarily proprietary systems that hinder interoperability. An exception is the common data link (CDL), used for downlink of Global Hawk sensor data and uplink of sensor control messages.

Common Data Link

In 1991, the DOD designated the common data link as the standard data link for imagery and signals intelligence. Thus, CDL is a key data link that enables sensor control and sensor exploitation for UAVs and manned ISR assets. In particular, CDL is used for the Global Hawk. The CDL uplink is secure, and jam-resistant with a rate of 200 kbps. The downlink operates at three rates: 10.71 megabits per second (Mbps), 137 Mbps, and 274 Mbps. Only the lowest downlink rate, 10.71 Mbps, is secure, however. The line-of-sight range is 200 km.

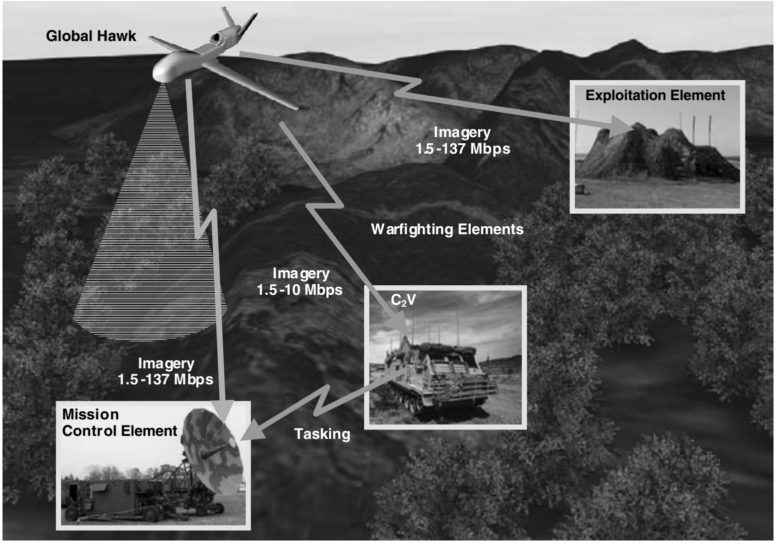

FIGURE 7.4 Global Hawk line-of-sight communications architecture. NOTE: C2V, command-and-control vehicle.

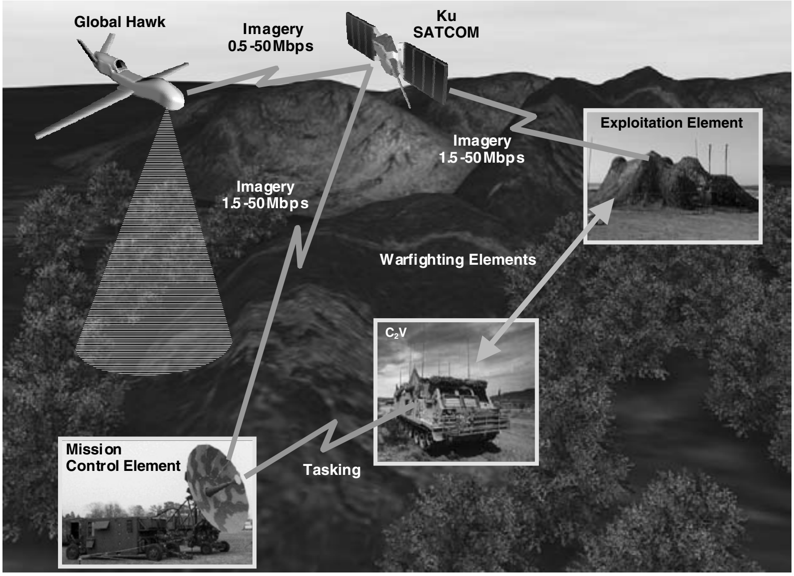

FIGURE 7.5 Global Hawk over-the-horizon communications architecture. NOTE: C2V, command-and-control vehicle.

CDL terminals operate in either the X or Ku band. The Navy has deployed a version of CDL, referred to as the common high-bandwidth data link (CHBDL), on its carriers.

There are a number of variants of CDL, including the tactical common data link (TCDL). TCDL terminals are smaller and cost less than other CDL terminals. Currently supported data rates are 1.5 to 10.71 Mbps at a 200 km range. In the future, TCDL is intended to support higher CDL rates as well. Navy platforms using TCDL include the Fire Scout, the multimission helicopter, the P3-AIP (Orion airplane, Antisurface Warfare Improvement Program), the aircraft carriers (CVs), the P3 Special Operations, and the S3B Surveillance System Upgrade model. Navy platforms planning to use TCDL include the Pioneer Improvement Program, the Broad Area Maritime Surveillance (BAMS) program, the multimission maritime aircraft, and the EP-3E. Thus, TCDL is an important data link for Navy ISR platforms in general and for UAVs (Fire Scout, Pioneer, and BAMS) in particular.

TCDL is intended as a standard to which multiple vendors can build interoperable hardware. While the committee strongly endorses such a standards-based approach in general and TCDL in particular, it was concerned to learn that the TCDL implementations of the various vendors are not truly interoperable. The problem is that there are four different TCDL implementations: Legacy TCDL, Packet Mux TCDL, Ethernet/Generic Framing Protocol, and the Asynchronous Transfer Mode/Cell Transfer Frame Format. As a result, no two CDL manufacturers had demonstrated interoperability of their equipment as of the date of the demonstration.[1]

Satellite Communications

Satellite communications are used for OTH relaying of UAV command-and-control data and sensor data dissemination. There are four segments to military satellite communications (MILSATCOM): ultrahigh frequency (UHF), superhigh frequency (SHF), extremely high frequency (EHF), and commercial services.

The UHF segment is a demand assignment multiaccess system with 48 kbps throughput. This segment supports mobile terminals and is used to provide connectivity to the warfighter. The UHF segment does not currently play any role in UAV communications.

The medium-data-rate SHF segment supports rates from 128 kbps to 1.544 Mbps and provides worldwide secure voice and high-data-rate communications between the United States and its network of military installations and other

[1]CAPT Dennis R. Sorensen, USN, Program Manager, Program Executive Office, Strike Weapons and Unmanned Aviation (PEO(W)) PMA-263, Naval Air Systems Command (NAVAIR), “PMA 263 Naval Unmanned Aerial Vehicles,” presentation to the committee, April 25, 2003.

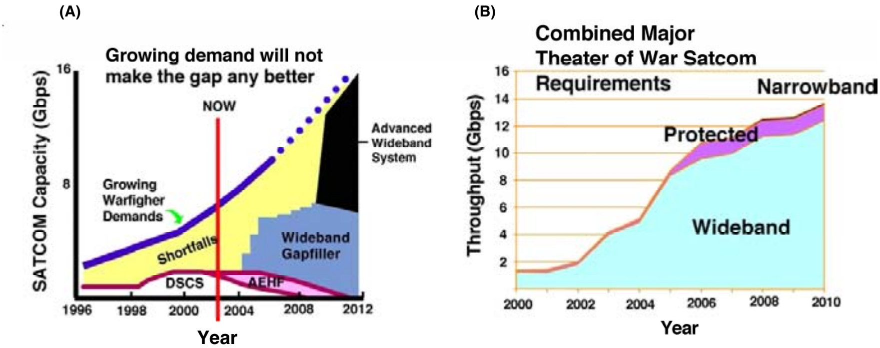

FIGURE 7.6 Projected military satellite communications (SATCOM) needs exceed capacity: (A) SATCOM capacity and warfighter demands, 1996-2012; (B) combined major theater of war satellite communications requirements, 2000-2010. NOTE: A list of acronyms is provided in Appendix D. SOURCE: Office of the Secretary of Defense. 2002. *Unmanned Aerial Vehicles Roadmap 2002-2027,* Department of Defense, Washington, D.C., December, p. 104.

government agencies. The high-data-rate SHF segment supports 1.544 to 24 Mbps throughput. The Global Broadcast System (GBS) is implemented on the SHF segment. GBS provides global coverage with one-way broadcast of information, including imagery, maps, weather information, and other data. GBS can be used to transmit near-real-time video from the Predator and other sources.

The EHF segment supports both low-data-rate 2.4 kbps and medium-data-rate 4.8 kbps to 1.544 Mbps throughput. It is a worldwide, secure, jam-resistant communications system for U.S. civilian and military leaders for command and control of military forces.

The current MILSATCOM architecture will be upgraded with additional capabilities later in this decade, provided by systems such as Wideband Gapfiller and advanced EHF (AEHF). However, as shown in Figure 7.6, even with these additional capabilities a capacity shortfall may exist. Commercial services are required to fill some of this shortfall. As the use of UAVs increases, the shortfall may have a significant impact on the availability of sensor information on demand.

In November 1993, the DOD released a report promoting the use of commercial SATCOM systems in all of the Services.[2] The goal was to augment military SATCOM to meet the total predicted communications throughput requirements. Commercial SATCOM systems operate in the C, Ku, and Ka bands. Examples include Iridium, Panamsat, Orion, Intelligence Satellite (INTELSAT), and International Maritime Satellite (INMARSAT).

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[2]Les Aspin, Secretary of Defense. 1993. *Report on the Bottom-Up Review*, U.S. Government Printing Office, Washington, D.C., October.

The Navy has been the sole Service to lease commercial SATCOM on a broad, Service-wide basis, under its Challenge Athena program (currently known as the Commercial Wideband Satellite Program (CWSP)). Satellite capacity leased under the CWSP is used to provide high-throughput (2.044 Mbps) connectivity to deployed naval forces. It is used for the dissemination of imagery, including imagery provided by UAVs.

Network-Centric Operations

The DOD and the Services are engaged in a series of initiatives aimed at eliminating communications bandwidth as a constraint, thereby providing the communications capabilities required to implement network-centric operations. When these initiatives come to full fruition, they will greatly facilitate command and control of UAVs and the dissemination of their data.

Global Information Grid

The Global Information Grid (GIG) is the vision of the Office of the Secretary of Defense (Networks and Information Integration) (OSD(NII)) for a single, secure-packet-based communications infrastructure providing seamless, end-to-end connectivity for all DOD platforms and facilities (Figure 7.7). The GIG is based on commercial technology (i.e., the commercial Internet Protocol (IP) is the fundamental transport mechanism). The GIG-Bandwidth Expansion (GIG-BE) program,[3] to be completed in FY04, will provide an optical, IP, terrestrial-based communications backbone to mitigate constraints in terrestrial bandwidth. This program will facilitate the collaborative exploitation and sharing of UAV data for cases in which the UAV has connectivity to one of the nodes interconnected by the GIG-BE.

Transformational Communications System

The Transformational Communications Office (TCO), jointly led by the Air Force and the Communications Directorate of the National Reconnaissance Office (NRO), was established in September 2002. The mission of this office is "to assure that we have communications compatibility across the DOD, the intelligence community, and NASA."[4] The goal is to create a new National Space

[3]For additional information, see the Web site <http://www.disa.mil/pao/fs/gigbe2.html>. Last accessed on April 1, 2004.

[4]Peter Teets, Undersecretary of the Air Force. 2002. "Special Briefing on the Opening of the Transformational Communications Office," Washington, D.C., September 3.

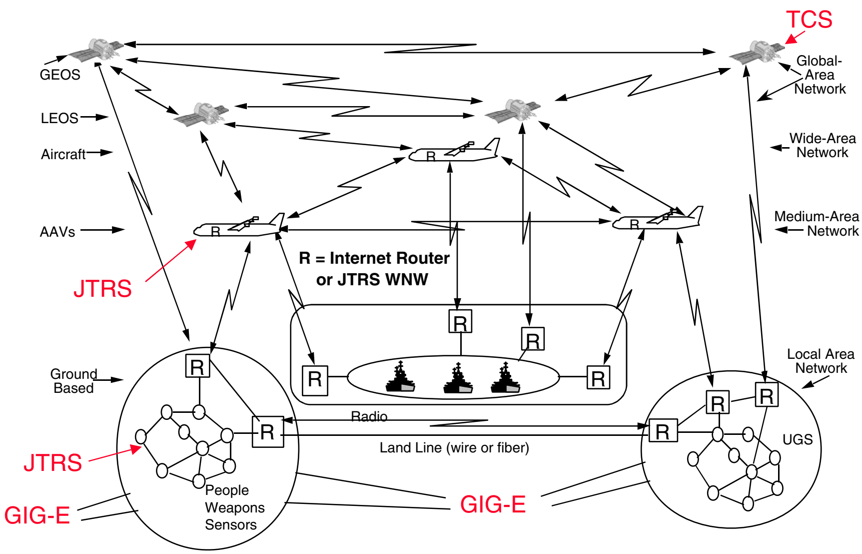

FIGURE 7.7 Global Information Grid concept. NOTE: A list of acronyms is provided in Appendix D. SOURCE: Michael S. Frankel, Deputy Assistant Secretary of Defense for Command, Control, Communications, Intelligence, Surveillance, and Reconnaissance (C3ISR), Space, and Information Technology, "Implementing the Global Information Grid (GIG): A Foundation for 2010 Net Centric Warfare," presentation to the committee, February 24, 2003.

Program architecture that ties together space-based and ground-based networks and that meet the military's growing need for bandwidth.

The Transformational Communications Architecture (TCA) is a subset of the GIG concept. TCA integrates mobile/tactical users and global intelligence services via IP. The physical-layer transport technologies are both radio frequency (RF) (EHF, X, Ku, and Ka band) and optical. Laser communications are envisioned for the high-rate users (e.g., sensor readout), while RF is for the tactical users. In particular, a laser communications terminal has been funded for the Global Hawk that would allow insertion of Global Hawk ISR data into the very high bandwidth, space-based network. A conceptual system architecture is shown in Figure 7.8.

The Transformational Communications System, the space component of the TCA, will have an initial operating capability (IOC) in FY09 and a final operational capability (FOC) in FY13. Thus, there is a significant gap in time between the upgrading of the terrestrial and space components of the GIG.

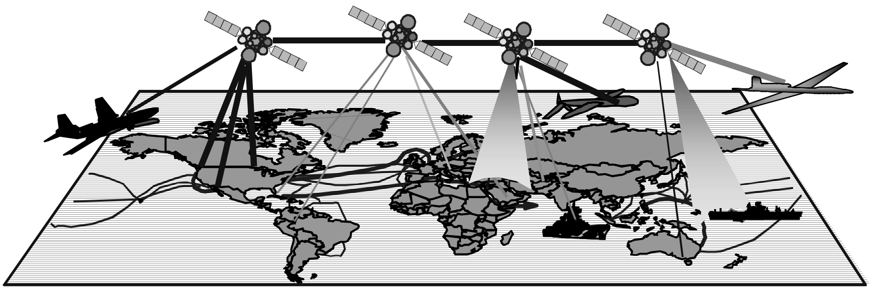

FIGURE 7.8 Transformational Communications Architecture. SOURCE: Michael S. Frankel, Deputy Assistant Secretary of Defense for Command, Control, Communications, Intelligence, Surveillance, and Reconnaissance (C3ISR), Space, and Information Technology, "Implementing the Global Information Grid (GIG): A Foundation for 2010 Net Centric Warfare," presentation to the committee, February 24, 2003.

FORCEnet

FORCEnet is the vision of the Chief of Naval Operations (CNO) for enabling network-centric operations for the Navy. According to the CNO's Strategic Studies Group, FORCEnet is the "operational construct and architectural framework for naval warfare in the information age, integrating warriors, sensors, command and control, platforms, and weapons into a networked, distributed combat force."[5] While broader in concept than just communications networks, it includes "dynamic, multi-path and survivable networks" as one of the capabilities to be provided. Network-centric operations and FORCEnet have been studied in greater detail in past and ongoing studies of the Naval Studies Board.[6,7]

While the committee applauds this vision, it is concerned that FORCEnet does not appear to have been translated into a concrete plan with adequate funding and the management structure necessary to realize the vision. Such a plan would need to provide for close coordination with OSD programs such as GIG-BE and Transformational Communications System, as well as Service-level programs such as the Air Force's Command and Control Constellation program.

[5]ADM Vern Clark, USN. 2002. "Sea Power 21: Projecting Decisive Joint Capabilities," *U.S. Naval Institute Proceedings*, Vol. 128, No. 10, pp. 32-41.

[6]Naval Studies Board, National Research Council. 2000. *Network-Centric Naval Forces: A Transition Strategy for Enhancing Operational Capabilities,* National Academy Press, Washington, D.C.

[7]National Research Council. 2005. *FORCEnet Implementation Strategy,* Naval Studies Board (in preparation).

Conclusions Concerning Unmanned Aerial Vehicle Communications

A plan for FORCEnet implementation with adequate funding and a management structure with the authority to implement the plan is needed. This plan can ensure the interoperability of naval systems and assure that the Navy's communications needs are addressed within the emerging context of the GIG. To ensure the interoperability of UAV data links, the Navy can work with OSD(NII) and the Services to establish a rigorous testing regime so that the CDL implementations of alternative vendors are interoperable. To have adequate bandwidth to ensure optimal, network-centric use of UAV sensor data, the Navy can make the necessary investments to connect to the Transformational Communications System when it becomes available. For the period prior to the IOC of this system, the Navy could continue utilizing commercial SATCOM, as it has successfully demonstrated with the Challenge Athena program.

Satellite communications can play a valuable role, but it is important to realize that the tremendous distance to geosynchronous satellites greatly reduces, typically by a factor of a million, the available bandwidth for a fixed antenna size and radiated power, when compared to point-to-point communications between UAVs and surface units. This is the reason that the Global Hawk and the Predator have such large, bulbous noses, containing ~1 m dishes to talk to the distant satellites with transmitters that use a major fraction of the available onboard auxiliary power.

By way of contrast, using only 20 cm (8 in.) antennas, a network of point-to-point UAVs and surface units can exchange a thousand times as much data with only 1/40th as much power. The need to limit the antenna footprint on ships, UAVs, and other units may make a theaterwide autonomous vehicle (AV) communications network that does not involve SATCOM very attractive. The role of AVs in expanding the bandwidth and capability of the command, control, communications, and computers (C4) network for theater operations may be as important as their role in intelligence, surveillance, reconnaissance, and targeting (ISR&T).

INTELLIGENCE, SURVEILLANCE, AND RECONNAISSANCE AND UNMANNED AERIAL VEHICLES

Current Capabilities and Issues

Operation Iraqi Freedom is the first war in which the long-standing goal of dominant situation awareness approached reality. Coalition ISR was ubiquitous, and the RQ-1 Predator, MQ-1 Predator with Hellfire, and RQ-4 Global Hawk were major contributors (Box 7.1). In addition, the Marines employed the Pioneer and Dragon Eye UAVs. Although there were many problems associated

BOX 7.1

Unmanned Aerial Vehicles Contributed to Dominant Situation Awareness

- Coalition Intelligence, Surveillance, and Reconnaissance (ISR) Facts (720-hour war)
  —U.S. and coalition ISR aircraft: 80
  —ISR sorties: 1,000
  —Battlefield images: 42,000
  —Hours of signal intelligence coverage: 2,400
  —Hours of full-motion video: 3,200
  —Hours of moving target indicator (MTI): 1,700
- Unmanned Aerial Vehicles
  —Hellfire missiles (MQ-1): 7
  —Predator (RQ-1): 9
  —Global Hawk (RQ-4): 1

SOURCE: Lt Gen T. Michael Moseley, USAF, Commander, Central Air Forces. 2003. *Operation Iraqi Freedom—By the Numbers,* Shaw Air Force Base, S.C., April 30.

with the prototype nature of Dragon Eye, overall it was highly regarded, and the Marines were happy to have it as a tool for intelligence gathering.

There is much room for improvement in ISR capabilities, particularly for the Navy and the Marine Corps. Important issues include the following:

- Identification of targets on the move,
- Detection of targets in foliage,
- Detection of targets in urban clutter,
- Detection and characterization of buried targets, and
- Detection and identification of nuclear, biological, and chemical (NBC) weapons materials.

Improvements in sensor packages for UAVs will help address some of these issues. For example, the Global Hawk Radar Technology Improvement Program (RTIP) radar will have increased accuracy and a higher update rate as well as high-resolution moving target indicator and moving target imaging modes that will help identify targets on the move. DARPA has developed a foliage-penetrating radar that is a potential sensor for the Global Hawk. Imaging laser detection and ranging (LADAR) under development by DARPA and the Services can help in areas with foliage and in urban areas. Multispectral imaging and hyperspectral imaging sensors are of potential utility for detecting targets in clutter, detecting and characterizing buried facilities, and detecting and identifying NBC materials.

Close-in Unmanned Aerial Vehicle ISR

Today, ISR systems gather information sensed at long standoff ranges, providing products such as images of the battlefield, communications intercepts, emitter geolocation and range, azimuth, and Doppler measurements of air and ground vehicle positions. This information provides a vital picture of the battlefield, but it does not provide the complete picture, particularly for difficult sensing situations including those cited above. To close the surveillance gap, a spectrum of short-range sensors will have to be developed and fielded to provide close-in measurements of hidden forces under trees and in underground facilities or to sense the presence of NBC agents. These very hard sensing problems can only be solved with high confidence by using short-range sensors, and the advances in unmanned autonomous systems are an enabling element of a whole new field of ISR. These new sensors will require low-burden means of access that can be provided for by micro air vehicles that fly to a point and "perch and sense" the environment from short or medium range, thereby solving the sensitivity and ambiguity problems associated with long ranges. Other unmanned systems that deploy unattended autonomous ground sensors will play a critical role in fulfilling the mission called Intelligent Preparation of the Battlefield.

For example, one application of particular interest is DARPA's program to provide under-the-trees surveillance by flying a small, vertical-takeoff-and-landing (VTOL) UAV under the tree canopy to search out enemy systems. These UAVs could use an array of imagery and short-range sensors, such as chemical-exhaust-sniffing sensors, magnetic sensors, and heat sensors. One can envision large numbers of these UAVs spanning out and searching out targets, geolocating them, and then popping up above the tree canopy to report back and call in remote fires.

Exploitation of Intelligence, Surveillance, and Reconnaissance Data

The ISR capabilities of current and planned UAVs, in conjunction with those of manned aircraft and satellites, hold the prospect of inundating analysts with more data than they can handle. For example, Figure 7.9 depicts the radar imagery and ground moving target indicator (GMTI) coverage that can be provided by the Global Hawk.

Anecdotal evidence provided to the committee indicates that the problem of saturating analysts with ISR data is not just a future concern, but a current reality. During its workup for Operation Iraqi Freedom, the USS *Truman* received imagery via the Global Broadcast System (GBS) at a rate of 4 Mbps. After 4 days, the *Truman* shut off the input data owing to the inability of its limited complement of analysts to keep up with the flow.

There are at least two possible approaches to keeping up with the increasing flow of ISR data:

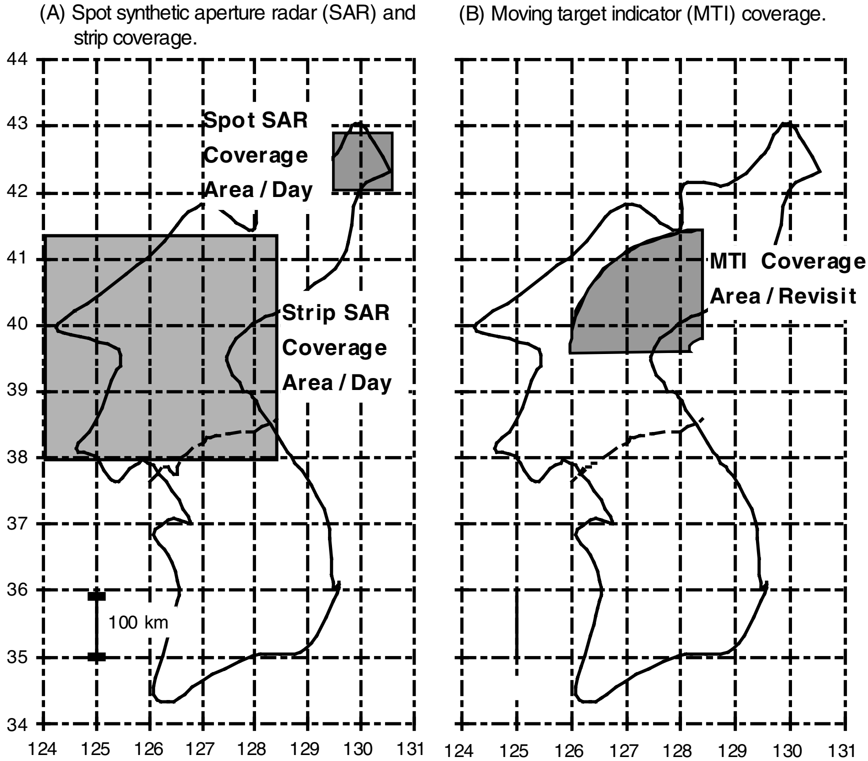

FIGURE 7.9 Global Hawk radar provides massive amounts of intelligence, surveillance, and reconnaissance data. NOTE: SAR, synthetic aperture radar; MTI, moving target indicator. SOURCE: Department of Defense.

- Increase the number of imagery and intelligence analysts analyzing the data, and
- Increase the productivity of the analysts or provide some screenings of the data fed.

Continually increasing the number of analysts is an expensive approach that is unlikely to be successful in the long run, given the proliferation of ISR data sources. However, one cost-effective, short-term approach is network-centric or reach-back operations, in which analysts onboard different ships and at different shore locations remotely collaborate to analyze ISR data. This approach will require sufficient communications bandwidth. Under this approach, enabled by modern communications and networking capabilities (see the preceding major section, "Unmanned Aerial Vehicle Communications"), the Navy's entire population of analysts could, in principle, be focused on a particular operation or operations. The committee understands that the Navy is evolving in this direction with the deployment of a Fleet Imagery Support Team at a location in the continental United States. The committee strongly endorses this development and urges its logical progression to a full implementation of joint, network-centric ISR exploitation and targeting. In developing this requirement, information push to users could be exploited to the maximum extent to permit parallel exploitation and time-critical targeting using ISR data.

Although network-centric operations can increase the effective number of analysts available to support a given operation, increasing levels of automation will be necessary in the long run to increase the productivity of these analysts. Also, an integrated approach is needed for onboard processing, reach-back operations, SATCOM capability, Transformational Communications System, and antennas. There has been a major investment by DARPA, ONR, and the R&D components of the other Services and the intelligence agencies in such technologies as the following:

- Image registration,
- Target detection,
- Automatic feature extraction,
- Change detection,
- Video object recognition and tracking,
- Automated target cueing,
- Automatic target recognition,
- Automatic battle damage assessment,
- GMTI tracking, and
- Multisensor fusion.

The problems being addressed are important and truly difficult, so a sustained, long-term R&D investment in these and related technologies is necessary. However, the committee believes that technologies for automated exploitation of ISR data are sufficiently mature to provide useful support to analysts and to benefit from real-world feedback. It therefore concludes that the Navy can more aggressively pursue the operational insertion of these technologies.

Conclusions Concerning Intelligence, Surveillance, and Reconnaissance and Unmanned Aerial Vehicles

Working with the DOD and the other Services, the Navy needs to develop a robust, joint, network-centric environment for exploitation and time-critical targeting using UAV and other ISR data. This environment needs to permit real-time collaboration by geographically dispersed analysts to maximize their utilization. To minimize time delays, a "task, post, process, use" (TPPU) approach in which data are pushed in parallel to users with a time-critical need and to intelligence analysts can be used in preference to a "task, process, exploit, disseminate" (TPED) approach in which users only obtain critical data after exploitation. To facilitate implementation of this environment, the Navy can actively participate in DOD activities developing standard data formats for ISR products to permit networked exploitation in a vendor-neutral environment.

The Navy needs a strong research effort focused on the development of automated tools for image registration, target detection, feature extraction, change detection, video object recognition and tracking, target recognition, automatic damage assessment, GMTI tracking, multisensor fusion, and other technologies for the exploitation of ISR data. As tools mature, the Navy can aggressively seek to insert them into operational systems, making sure that researchers are involved in these efforts to obtain real-world feedback.

INTEROPERABILITY ISSUES FOR AUTONOMOUS VEHICLES

In the context of emerging 21st-century battlespace operations, systems are interoperable if users can easily and confidently make them work together in reasonable combinations that have never been tried before. With enough application-specific interface boxes, one can make almost anything interact (to some limited extent) with anything else. From an operational perspective, interoperability problems show up when warfighters try to do something innovative, reasonable, and useful, and it does not work (for whatever reason). If the Navy is to take maximum advantage of autonomous vehicles to support its future operations, there will be many such vehicles of many types, and they will need to work together effectively, preferably in any reasonable ad hoc combination. Human attention is already a scarce and precious resource in military operations; interoperable systems reduce the human attention required to accomplish a mission, while systems that interoperate poorly increase it. Hence, a goal for autonomous vehicles will be that they can interoperate—not only communicating data that they collect but, eventually, coordinating objectives and tasks. Highly autonomous systems must be able to interoperate with each other as well as with their human supervisors. These goals are still distant, but they provide an important reference for current activities.

Systems may fail to interoperate today at many technical levels: they may be unable to interconnect physically because they use different connectors or different frequencies, they may be unable to exchange information because they use different modulation formats, or they may be unable to communicate effectively because they speak different languages at any one of several levels of communication protocols. Perhaps the greatest success of Internet technology is the agreement on one single, intermediate-level protocol suite—known as Transmission

Control Protocol/Internet Protocol (TCP/IP)—that has facilitated the end-to-end interoperability, from a communications networking perspective, of a wide variety of devices that feature different physical interconnection formats and different communication protocols at many levels. However, the ability to transport IP packets successfully, end-to-end through a network, is only one factor in achieving end-to-end application viability. Furthermore, even the end-to-end interoperability of heterogeneous networks that employ IP and the interoperability of computers that employ TCP on an end-to-end basis could be jeopardized by the employment of some proposed mechanisms within networks to manage quality of service provided by communications networks.

This section develops and describes the committee's conclusions in the area of creating interoperable systems of AVs. One major area of concern is the interoperability of communications and control systems. During Operation Iraqi Freedom, a wide variety of communications equipment in use led to information overload (when information was received over too many different networks) and at the same time to a need to hop-scotch among different, noninteroperable systems at moments when either of the communicating parties had different subsets of equipment available or some systems could communicate successfully and others could not. These problems reportedly caused tactical imagery provided by Dragon Eye to be rendered useless to headquarters in several cases because of its late delivery.

AV control-system interoperability and the need to establish common architectures for the control of AV systems were recognized as an issue by the committee. Control systems will, appropriately, evolve separately for vehicles designed for different environments; yet a continuing oversight and, to some extent, coordination of these architectures is perhaps the only way to prevent future interoperability problems among them.

A second major area of concern for interoperability is that of trust. This term is used to incorporate concerns about the integrity, availability, and confidentiality of data and control signals passed between AVs and to humans, perhaps from many different nations in a coalition operation. A particularly critical control signal, and one that will require human-in-the-loop trust for the foreseeable future, is the authorization to release weapons. To achieve interoperability, from the perspective of warfighters who use network-based applications (e.g., AVs), one must demonstrate that the same level of trust that has been determined (by design and testing) to exist when "standard" combinations of systems are used together will also be present when systems are used together in ad hoc combinations by these warfighters. There is a big difference (both from the point of view of design principles, and from the point of view of usefulness to warfighters) between systems that have been determined to be trustworthy in certain combinations and systems that have been designed and proven to be trustworthy in ad hoc combinations.

In addition, the committee is concerned with the trustworthiness of AV systems themselves as they increasingly operate in the same spaces where manned systems are operating. It is highly likely that some form of certification will be required for these systems. The Predator system has bypassed these concerns, successfully using commercial airports in several countries, but only by having a human pilot operating the aircraft from the ground. This level of human-intensive control seems an unlikely long-term path for UAV development. UAV developers are addressing this problem, working among themselves and with the Federal Aviation Administration to agree on viable approaches, but there is much to be done. It is worth noting that a principal disincentive today for the deployment of more highly automated, and almost certainly more effective accident-avoidance systems in the context of commercial and private automobiles, is concern about how such systems may affect vendor liability. These concerns are likely to be manifest in all AV domains eventually, and only when such systems can be in some way certified to be trustworthy will they gain widespread use.

Communications Issues as Constraining Factors on Interoperability

A system that interoperates with another successfully at the protocol and even the human-interface level may fail if it imposes an unacceptable resource burden on whatever it is interoperating with. UAVs conducting persistent ISR may manifest this problem, since today's sensors can generate data at a substantial rate; future hyperspectral sensors will only increase this rate. The committee understands that some officers have been unwilling to accept downlinks from such UAVs because they could saturate the bandwidth available to the ship. Adequate satellite communications, either military or commercial, are needed to meet this challenge. The Navy is learning how to structure its communications environment so that ships can retrieve needed imagery quickly and effectively from shore-based archives that receive the data from UAVs and other sources.

Other potential bandwidth bottlenecks that may affect UAV interoperability include the umbilical link (if any) between the UAV and suitable relay points, either for transferring data from the UAV or for relaying sensor and control information. As the number of UAVs increases, communications may also be limited by the aggregate capacity of shared relay nodes or of shared, high-capacity wireless backbone trunks, both terrestrial and satellite. To address these issues, UAV systems engineering must integrate network capacity planning with ISR platform planning throughout the DOD. Interoperability is achieved only through effective systems engineering that takes both the human and automated aspects of the system into account.

Today's networks lack adequate network-management technologies and methodologies to support the effective use of a shared battlespace network by a diverse set of applications, including plaintext messaging, real-time control, imagery transport, and others. These applications exhibit diverse requirements for latency, bandwidth, and priorities. This network-management problem is shared by the commercial cellular industry, which is in the process of upgrading its networks to support applications such as e-mail, Web access, audio, and video streaming on a common cellular platform that also supports telephones. The commercial cellular industry has at stake tens of billions of dollars of investments in spectrum acquisition and hundreds of billions of dollars in market capitalization, and it is investing heavily in the development of solutions for managing the efficiency of utilization of its networks while providing the right kinds of heterogeneous qualities of service that its customers may demand (and be willing to pay for). Since the cellular industry does not know how customers will actually use these emerging "third-generation" cellular networks and what different types of services they will demand (and be willing to pay for), it faces essentially the same set of network-management challenges as the Navy and the rest of DOD faces. Thus, commercial industry is a source of network-management technologies and methodologies that can be used by the DOD as they emerge.

Trust as a Constraining Factor on Interoperability

Because it has proven exceedingly difficult to ensure that a piece of computing equipment can successfully separate users cleared at some level from information classified above that level, we live in a world of military systems that are significantly replicated and segregated by security level. The introduction of AVs into this world (e.g., whether a sensor is carried by a U-2 or a Global Hawk) may not seem to raise new issues, since the sensors onboard the U-2 are already controlled from the ground and the integrity and confidentiality of the data transmitted are cryptographically protected. However, prototype AVs are often developed without protection of their control signals, simply because they are prototypes. If these prototypes are pressed into field service, these links will be vulnerable. In the information-assurance world, the concept of establishing a "trusted path" to the computers that control the AV should be adhered to. The inability to establish a trusted path between systems exchanging sensitive information can prevent their interoperation.

The ability of UAVs to collect very large volumes of data during a long mission, combined with limits on downlink bandwidth and even on human capacity to analyze images, may lead to designs in which flying image archives are queried by diverse groups of users. These users may even be members of coalitions with different interests and clearances. This scenario would, in effect, require an autonomous, multilevel image archive, capable of authenticating users. Further, if the UAV carrying the archive were shot down, the data in the archive would need to be protected against enemy exploitation.

UAVs must be recognized as software-intensive systems. As such, particularly as their utility increases, they may be seen by opponents as potential targets of cyberattacks. Even in the area of real-time control, there is a great financial incentive today to embrace commercial off-the-shelf software. If the software is proprietary, it may be difficult to ensure that its production has not been compromised. Even if the source code is available, ensuring that the software is free of security-relevant flaws has proven an extremely challenging task. Again, prototype UAVs may be developed without taking these issues into account, but pressing such prototypes into service when they are seen to provide a valuable function means accepting a level of risk that the fielded prototype could be subverted, which may again limit their interoperability.

Conclusions Concerning Interoperability Issues

Interoperability is not something that the Navy can achieve unilaterally; it must be achieved working in partnership with the DOD and the other Services. In the near term, the Navy needs to carry out the following:

- Adopt and adapt emerging, commercial "third-generation" wireless network-management technologies and methodologies for managing quality of service in a mixed-application wireless networking environment;
- Integrate network capacity planning with ISR platform planning;
- Ensure that UAV designs anticipate requirements to support payloads that may operate at a variety of security levels; and
- Ensure that the integrity and authenticity of UAV control signals are protected against cyberattacks, including attacks targeted at software development processes.

Over the longer term, the Navy needs to do the following:

- Create an interoperability policy that has teeth (funding control) and that takes into account the need to modify business and contractual relationships with suppliers in order to make interoperability feasible from a business perspective, and
- In development of interoperability polices, include the consideration of issues of establishing trusted paths to UAVs (e.g., for vehicle control and for weapons-release authorization).

UNMANNED SPACE SYSTEMS

In 1957, the Soviet Union launched Sputnik, a small, unmanned space vehicle (or satellite), which circled Earth emitting a simple radio beacon signal. That signal was heard around the world, setting off the race to conquer space. President Dwight Eisenhower, recognizing both the promise and threat that space systems posed for the United States, created a new defense agency, the Advanced Research Projects Agency (ARPA), whose sole mission was to prevent technological surprise. The first directive given the new agency by President Eisenhower was to initiate space R&D programs for both unmanned and manned space systems that would enable the United States to catch up with and surpass the Soviet Union in the exploitation and use of space. In the first year, ARPA created and focused development efforts in communications satellites with the Army, navigation satellites with the Navy, and reconnaissance satellites with the Air Force and the Central Intelligence Agency. Today the United States benefits from intelligence, surveillance, reconnaissance, navigation, and communications functions all based on unmanned space vehicles or satellites. These unmanned space systems—all descendants of these early unmanned space systems—have not only lived up to their initial promise, but far exceed the wildest dreams of their visionary creators.

The U.S. military continues to expand the use of space systems for tactical military purposes. This was clearly evident in Operation Iraqi Freedom, during which the U.S. military's use and dependence on spaceborne systems affected every operation and did so in a nearly transparent fashion. When asked about the importance of space systems to him, one soldier was quoted as saying, "I do not need any space systems. All I need is my M-16 and my Pluger" (the Army's GPS receiver unit for dismounted soldiers).

The Navy's use of unmanned space systems in Operation Iraqi Freedom ranged from GPS navigation of ships, aircraft, and Marines; to fleet and over-the-horizon satellite communications; to the exploitation of national ISR capabilities supporting reconnaissance, targeting, and bomb damage assessment. Over 25 percent of U.S. air-delivered munitions relied on GPS for guidance.

Today, space systems are limited by the ISR coverage and responsiveness they provide to the tactical users. Although there was a large use of space ISR in Operation Iraqi Freedom, there is still much room for improvement. The brownout conditions caused by sandstorms highlighted the importance of all-weather sensors, since optical sensors were blinded by the sandstorms. U.S. warfighters found that the Joint Surveillance Target Attack Radar System (JSTARS) ground moving targeting radar sensors were able to keep operating and provided key indications of Iraqi fedayeen troop movements under the supposed cover of the sandstorm. This constant vigilance enabled by all-weather radar sensors enabled U.S. troops to engage the enemy while still moving during the brownout, thus delivering a decisive and tremendously debilitating blow. Other examples of the importance of real-time surveillance and imagery were evident throughout the Iraqi theater. Being able to provide this kind of timely awareness of adversaries throughout a theater will be key to any future battles in which the size and scale of the country is not so constrained.

Future conflicts might also see the increased use of systems designed to counter imagery, navigation, or other space assets. Iraq also displayed systematic use of activity scheduling, which was not always successful in the movement of banned equipment around the country before the war began. This weakness in

U.S. space systems is due to the predictability of the orbits of the nation's satellites and constrained by the limited amount of fuel onboard, such that maneuvering a satellite to reduce predictability is not an option.

Autonomy in Space

Future space systems concepts are being developed by DARPA and the National Aeronautics and Space Administration (NASA) to provide unmanned routine access to satellites for refueling, repair, and systems upgrade. This post-launch access will allow the refueling of satellites so that they can be maneuvered, upgraded, or repaired. Such new capabilities will enhance the utility and reduce the life-cycle cost of U.S. space systems. For example, it may be possible to cut the costs for unmanned space operations through the use of an on-orbit, unmanned servicing infrastructure to extend useful satellite life. Presently, satellites are deorbited, and all hardware onboard is destroyed at the end of useful life. Expensive items such as optics, motors, and various subsystems are discarded, and the high cost of launching a replacement spacecraft is incurred. The replenishment of "commodities" such as fuel and the replacement of some spacecraft components while on orbit may provide significant life-cycle cost savings and enable spacecraft to be upgraded rather than hurtling toward obsolescence immediately after their use. These commodities would be delivered to orbit via low-cost, mass-produced launchers in order to realize very low cost to orbit; robotic space "tugs" would deliver the commodities to operational spacecraft. The ability to refuel spacecraft also provides a tremendous new capability for military spacecraft and enables them to turn vulnerability into strength by reversing their vulnerability and predictability. One can envision future Navy systems that are able to optimize orbits to provide tactical surprise or optimize coverage for a particular theater on a continuing basis.

Space-Based Radar

Another program that could hold great benefits for Navy and Marine Corp systems is the Space Based Radar program.[8] This transformational Air Force/National Reconnaissance Office program is designed to achieve theaterwide persistent situational awareness by a combination of ground movement surveillance via GMTI radar and reconnaissance imagery via SAR. The system as envisioned would consist of a constellation of radar satellites, which would provide constant worldwide coverage of multiple theaters of interest around the globe.

[8]For additional information, see the Web site <http://www.losangeles.af.mil/smc/pa/fact_sheets/sbr.htm>. Last accessed on April 1, 2004.

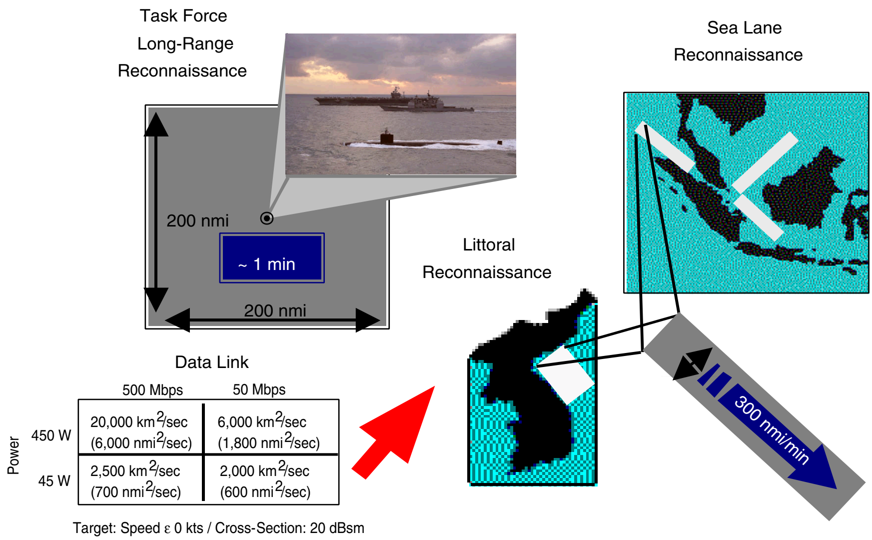

FIGURE 7.10 Space-based radar could provide a powerful capability for maritime surveillance. SOURCE: David Whelan, Discoverer II Program, Defense Advanced Research Projects Agency, 1999.

This space-based radar (SBR) is currently being designed with ground surveillance in mind, but its potential for ocean surveillance is equally promising (Figure 7.10). A system designed to track ground vehicles at slow speeds in various terrain environments could also be designed to measure small to medium-sized vehicles. Continuous low-power radar modes could allow a system, designed for limited radar operation time per orbit on smaller ground targets, to operate searching and tracking of larger ocean vessels in a continuous fashion during the systems nominal downtime. This way, the system could collect broad-area surveillance data while traversing open oceans, with little impact on its land surveillance functions and missions. Likewise, considerable Navy experience and expertise with radar sea clutter modes could enhance the SBR system's performance in littoral environments. Such missions can typically be integrated into a system design early in a program with reasonable impacts on overall system design, but if they are not integrated in the program's early phases, it can be difficult and expensive to attempt integration later.

Early involvement by Navy and Marine Corps personnel in the Air Force/NRO program could present a tremendous opportunity for the Navy to get its truly global surveillance needs and future requirements integrated into the SBR system.

Conclusions Concerning Unmanned Space Systems

To enhance its capabilities for Broad Area Maritime Surveillance (BAMS), the Navy could negotiate a Memorandum of Agreement with the Air Force to integrate ocean surveillance modes into the Space Based Radar program. The Navy could develop and exercise connectivity and systems to exploit SBR surveillance data and to plan and control SBR maritime surveillance missions, and it could work with unified combatant commanders to develop plans and procedures for obtaining access to SBR resources when required.

CONCLUSIONS AND RECOMMENDATIONS

FORCEnet

It is necessary for the Navy to develop an adequately funded FORCEnet implementation plan and management structure in order to coordinate with the Office of the Secretary of Defense (OSD) and other Services with respect to requirements and interoperability; to support the Office of the Secretary of Defense (Networks and Information Integration) (OSD(NII)) in its Transformational Communications efforts, including providing the necessary connectivity to the Global Information Grid-Bandwidth Expansion (GIG-BE) and Transformational Communications System; and to conduct the necessary systems engineering, assign requirements to Navy platforms, and provide funding for satisfying these requirements.

Exploiting Unmanned Aerial Vehicle-Derived Intelligence, Surveillance, and Reconnaissance Imagery

The committee finds that to facilitate the exploitation of unmanned aerial vehicle data, it is necessary to develop a robust, joint, network-centric TPED/TPPU environment, employing standard data formats for ISR products to permit networked exploitation. Research needs to be focused on the development of automated tools for tracking, fusion, automatic target recognition, and sensor management. Emerging tools need to be deployed in a spiral development approach so as to benefit from available capabilities and to provide feedback to researchers.

In addition, the current challenges in the exploitation of autonomous vehicle ISR information, coupled with the expected future explosion in ISR information generation by autonomous vehicles, require the development of a new approach to mitigate ISR analyst saturation. Today's command, control, communications, computers, intelligence, surveillance, and reconnaissance (C4ISR) systems and the autonomous vehicle control systems that they task are loosely coupled. Furthermore, a tight vertical integration of autonomy capability, between the command-and-control system and the autonomous vehicles they will task and control, is needed for future autonomous vehicle development. This will enable more effective, survivable, and affordable autonomous vehicles that can respond with agility to rapidly changing conditions in order to enable capabilities, such as the following:

- Route deconfliction with other vehicles operating in the same space,
- Exploitation and prosecution of targets of opportunity,
- Reduction in the number of "friendly fire" incidents,
- Real-time, command-level retasking to higher-priority objectives, and
- Rapid response to system failures that impact mission objectives.

Control and Interoperability of Unmanned Aerial Vehicles

An interoperability policy with "teeth" (funding control) is required that takes into account the need to modify business or contractual relationships with suppliers in order to make interoperability feasible from a business perspective. In the development of interoperability policies, the consideration of issues of establishing trusted paths to unmanned aerial vehicles (e.g., for vehicle control and for weapons-release authorization) is needed.

It is necessary to support ongoing DOD efforts to define standards and protocols for UAV control—in particular, the UAV Planning Task Force and the UAV Interoperability Integrated Product Team. To cope with the increasing complexity of UAV missions and to take full advantage of the potential for reduced manning, an aggressive research program in intelligent autonomy is required. This effort can be conducted in coordination with the efforts of the Defense Advanced Research Projects Agency and the Air Force.

The committee finds that the achievement of the Naval Services' future vision requires the standardization of interfaces, protocols, and the development of common architectures for autonomous vehicle communications and control.

Space

The Department of the Navy needs to expand its initial interaction and involvement in the Space Based Radar program. To enhance its capabilities for Broad Area Maritime Surveillance (BAMS), the Navy needs to negotiate a Memorandum of Agreement with the Air Force to integrate ocean surveillance modes into the space-based radar (SBR). The Navy could develop and exercise connectivity and systems to exploit SBR surveillance data and to plan and control SBR maritime surveillance missions, and it could work with unified combatant commanders to develop plans and procedures for obtaining access to SBR resources when required.

Recommendations Concerning Network-Centric Operations

Recommendation: The Assistant Secretary of the Navy for Research, Development, and Acquisition (ASN(RD&A)) should formulate and execute a comprehensive plan to eliminate or significantly mitigate deficiencies in command, control, communications, computers, intelligence, surveillance, and reconnaissance systems equipment and infrastructure, including communications bandwidth, that now limit the use of modern intelligence, surveillance, and reconnaissance (ISR) systems for autonomous vehicles. Specifically:

Develop an Adequately Funded FORCEnet Implementation Plan. The Chief of Naval Operations (CNO) and the Commandant of the Marine Corps (CMC) should coordinate an adequately funded FORCEnet implementation plan and management structure to interact with the Office of the Secretary of Defense and other Services on the requirements and interoperability necessary to support network-centric operations.

Facilitate Exploitation of Unmanned Aerial Vehicle Data. The CNO and the CMC should take measures to facilitate the exploitation of unmanned aerial vehicle (UAV) data by developing a robust, joint, network-centric "task, process, exploit, disseminate/task, post, process, use" (TPED/TPPU) environment, utilizing standard data formats for ISR products to permit distributed exploitation. Automatic target recognition-like techniques should be explored so as to more rapidly screen large volumes of electro-optical/infrared and synthetic aperture radar imagery generated by ISR UAV systems such as the Global Hawk. The Naval Network Warfare Command and the Space and Naval Warfare Systems Command should implement an organizational structure and a systems development approach that promotes a tighter vertical integration of command-and-control systems (e.g., C4ISR) with the autonomous vehicle control systems that they task.

Define Standards and Protocols for Unmanned Aerial Vehicle Control. The ASN(RD&A) should continue to support ongoing Department of Defense efforts to define standards and protocols for unmanned aerial vehicle control, in coordination with the efforts of the Defense Advanced Research Projects Agency and the Air Force.

Expand Involvement in the Space Based Radar Program. The Department of the Navy should expand its initial interaction and involvement in the Space Based Radar program to determine if that program is in the best interest of the Navy in terms of satisfying the Navy's ocean surveillance requirements. Communications connectivity and analysis systems necessary to exploit space-based radar (SBR) surveillance data and to plan and control SBR maritime surveillance missions should be given particular consideration. The CNO should direct liaison with both the Joint Staff (in particular, J6—Joint Staff experts on command, control, communications, and computers) and the unified combatant commanders in order to develop plans and procedures for obtaining access to SBR resources if required.

Appendixes

A

Biographies of Committee Members and Staff

John J. Deyst (Chair) is professor of aeronautics and astronautics at the Massachusetts Institute of Technology (MIT). During his 35 years at the Charles S. Draper Laboratory and MIT, Dr. Deyst's research efforts have focused in the areas of estimation theory, control theory and methods, fault-tolerant systems, guidance technologies, sensors for aerospace vehicles, and lean aerospace development and production. His recent interests include autonomous and information systems for aerospace vehicles—in particular, those systems with application to unmanned aerial vehicles (UAVs)—and center on the development, verification, and validation of avionics hardware and software. Dr. Deyst is a fellow of the American Institute of Aeronautics and Astronautics and has served on numerous scientific boards and advisory committees. He received his S.B., S.M., and Sc.D. degrees from MIT. Currently he leads the development team for the MIT/Draper Laboratory Parent-Child UAV program.

Neil Adams is the director of industrial research and development at the Charles S. Draper Laboratory, where he is responsible for managing a variety of the laboratory's technology investment and development programs. Mr. Adams recently served as principal systems engineer in the Systems Engineering and Evaluation Directorate and as technical director for autonomous systems at the Draper Laboratory. In these latter capacities, he was responsible for coordinating the internal research and development efforts relating to the development of advanced intelligent autonomy technology. Mr. Adams previously served as the Draper Laboratory's technical director for the Office of Naval Research (ONR) Uninhabited Combat Air Vehicles Demonstration Program, the Defense Advanced Research Projects Agency (DARPA) Small Aerial Reconnaissance Vehicle Program, the DARPA Micro Air Vehicle Program, and the ONR Intelligent Autonomy Program.

W.R. (Will) Bolton is technical director for the Atmospheric Radiation Measurement-Unmanned Aerospace Vehicles Program, a U.S. Department of Energy collaboration involving industrial, academic, and national laboratory participation; and manager of the Exploratory Systems Technology Department at Sandia National Laboratories. The Atmospheric Radiation Measurement-Unmanned Aerospace Vehicles Program was established to investigate the interaction of clouds and solar energy in the atmosphere and to demonstrate the utility of unmanned aerial vehicles (UAVs) for atmospheric research. Dr. Bolton has an extensive background in aerodynamics, particularly in regard to UAV stability and control. Prior to joining Sandia, he was an engineer at the Boeing Military Airplane Division. His professional experience, in both technical areas and program management, has included responsibilities for a number of advanced development and exploratory projects in areas ranging from parachute aerodynamics to the high-speed penetration of water, ice, and Earth by suborbital missile payloads.

Roy R. Buehler, an independent consultant, retired from Lockheed Martin Aeronautical Systems, where he managed Lockheed's U.S. Customs Service Line of Business. Mr. Buehler's background is in antiair and antisurface warfare and airborne early-warning systems. He has more than 30 years of experience in industry and government as an experimental test pilot, business planner, and program manager in the start-up of new aircraft programs, such as those for the F-111, F-14, F-18, A-6, and F-22/Naval Advanced Tactical Fighter. He served in the Navy as a carrier fighter pilot and also as an experimental test pilot and major program manager. Mr. Buehler is a member of the Society of Experimental Test Pilots.

Armand J. Chaput is a senior technical fellow at Lockheed Martin Aeronautics Company in Fort Worth, Texas, where he provides technical support to a range of advanced aerospace projects. Dr. Chaput also teaches unmanned aerial vehicle design at the Sejong University-Lockheed Martin Aerospace Research Center in Seoul, Korea. His previous assignments at Lockheed and predecessor companies include those as Uninhabited Combat Air Vehicles Integrated Product Team lead; chief engineer for the Lockheed/McDonnell Douglas/Northrop AFX (modernization program for attack fighter aircraft, since cancelled) team; chief engineer for the National Aero-Space Plane; and manager of the General Dynamics Advanced Design Organization. Prior to joining Lockheed, he was at the Central Intelligence Agency where he had both operational and technical assignments and was on active duty as an Army Ordnance Corps officer. Dr. Chaput has served on numerous scientific boards and advisory committees, including the American Institute of Aeronautics and Astronautics Aircraft Design Technical Committee and the Air Force Scientific Advisory Board. He received B.S., M.S., and Ph.D. degrees in aerospace engineering from Texas A&M University.

John C. Fielding retired in July 2003 as vice president of Raytheon Electronic Systems, where he had directed the Advanced Systems Group, a staff function in the Electronic Systems Headquarters. Prior to joining Raytheon, Mr. Fielding was an associate division head and member of the steering committee at the MIT Lincoln Laboratory, where he worked on space-based defense and National Aeronautics and Space Administration programs, as well as on studies involving cruise missile defense, counterstealth, relocatable strategic targets, and air traffic control. For a period in the 1970s he left MIT and joined the General Research Corporation, where he led a technical support effort to the Arms Control and Disarmament Agency in the negotiation of the Anti-Ballistic Missile Treaty. Mr. Fielding has served on numerous scientific boards and advisory committees, including participation in studies for the Defense Science Board and the National Research Council's (NRC's) Committee on Alternative Futures for the Army Research Laboratory.

James R. Fitzgerald, Vice Admiral, USN (Ret.), retired from the U.S. Navy after 35 years of service, principally within the surface force. During his career, Admiral Fitzgerald served in a number of senior leadership capacities including the following: director of the Antisubmarine Warfare Division, Chief of Naval Operations' staff; current operations officer for the Joint Chiefs of Staff; commander of the USS *Carl Vinson* Battle Group; and deputy commander in chief of the U.S. Pacific Fleet. His last assignment prior to retirement was as inspector general for the Department of the Navy. Currently, Admiral Fitzgerald is a member of the senior technical staff at the Applied Physics Laboratory of the Johns Hopkins University, where his interests center on undersea warfare. Admiral Fitzgerald has a B.S. in business administration from the University of Florida and an M.S. in engineering acoustics from the Naval Postgraduate School, and is a graduate of the National War College.

Charles A. (Bert) Fowler, an independent consultant, is retired senior vice president at the MITRE Corporation, a federally funded research and development center serving the government on issues relating to national security. Mr. Fowler, a member of the National Academy of Engineering, has an extensive background in military systems utilizing radar, sensor, and countermeasure technologies. Mr. Fowler began his career as a staff member of the Radiation Laboratory at MIT, where he participated in the development and testing of the ground control approach radar landing system. He later went on to engineering and management positions at MIT's Artificial Intelligence Laboratory, the Department of Defense, and Raytheon Systems Company before joining MITRE in 1976. Mr. Fowler is a fellow of the American Institute of Aeronautics and Astronautics, the American Association for the Advancement of Science, and the Institute of Electrical and Electronics Engineers. He received his B.S. in engineering physics from the University of Illinois.

Robert H. Gormley, Rear Admiral, USN (Ret.), is president of the Oceanus Company, a technology advisory and business development firm serving clients in fields of aerospace, defense, and electronics. Admiral Gormley is also senior vice president of Projects International, Inc., a Washington-based company that assists U.S. and foreign clients in developing trade and investment opportunities. Earlier, as a career officer and naval aviator, he commanded the aircraft carrier USS *John F. Kennedy*, a combat stores ship, an air wing, and a fighter squadron during the Vietnam War. Additionally, he served in the Navy's Operational Test and Evaluation Force, Office of the Assistant Secretary of Defense (Systems Analysis); and as chief of studies, analysis, and wargaming for the Joint Chiefs of Staff. Admiral Gormley has an extensive background in aviation technologies, with emphasis on unmanned aerial vehicles, airborne reconnaissance systems, aircraft survivability, and vertical/short takeoff and landing aircraft. He regularly participates in national security studies undertaken by the NRC and has been a member of study panels of the Defense Science Board and the Naval Research Advisory Committee. Admiral Gormley studied at the U.S. Naval Academy and Harvard University and was awarded degrees by both institutions.

Michael R. Hilliard is on the research staff of the National Transportation Research Center at the Oak Ridge National Laboratory (ORNL). During Dr. Hilliard's tenure at ORNL, his research interests have focused on the implementation of development models for complex systems, the design of optimization and artificial-intelligence-based algorithms, and the implementation of decision-support systems for public agencies. Dr. Hilliard led a major effort at ORNL to provide the U.S. Air Force Air Mobility Command with state-of-the-art planning and scheduling tools. Recently, he worked with a team of researchers from the University of Tennessee to analyze the supply-chain practices of the Defense Logistics Agency. Currently, he is working with the Army Corps of Engineers developing automated tools to analyze the flow of traffic on the inland waterway system. Dr. Hilliard earned a Ph.D. in operations research and industrial engineering from Cornell University.

Frank A. Horrigan retired from the technical development staff for sensors and electronic systems at Raytheon Systems Company. He has broad general knowledge of all technologies relevant to military systems. A theoretical physicist, Dr. Horrigan has more than 35 years of experience in advanced electronics, electro-optics, radar and sensor technologies, and advanced information systems. In addition, he has extensive experience in planning and managing industrial research and development investments and in projecting directions of future technology growth. Dr. Horrigan once served as a NATO Fellow at the Saclay nuclear research center in France. Today he serves on numerous scientific boards and advisory committees and is a member of the NRC's Naval Studies Board.

Harry W. Jenkins, Jr., Major General, USMC (Ret.), is director of business development and congressional liaison at ITT Industries, where he is responsible for activities in support of tactical communications systems and airborne electronic warfare between the Navy, Marine Corps, Coast Guard, National Guard, and appropriate committees in Congress. General Jenkins's operational background is in expeditionary warfare, particularly in regard to its mission use of command, control, communications, computers, and intelligence (C4I) systems. During Desert Storm, General Jenkins served as the commanding general of the Fourth Marine Expeditionary Brigade, where he directed operational planning, training, and employment of the ground units, aviation assets, and command-and-control systems in the 17,000-person amphibious force. General Jenkins's last position before retirement from the U.S. Marine Corps was as director of expeditionary warfare for the Chief of Naval Operations, where he initiated a detailed program for C4I systems improvements for large-deck amphibious ships, as well as managing all programs of naval mine warfare and reorganizing the Navy's unmanned aerial vehicle efforts for operations from aircraft carriers and amphibious ships. He is a member of numerous professional societies, including the Marine Corps Association, Marine Corps Aviation Association, Expeditionary Warfare Division of the Naval Defense Industry Association, Navy League, and Adjutant Generals Association of the United States. General Jenkins is a member of the NRC's Naval Studies Board.

David V. Kalbaugh is assistant director for programs at the Johns Hopkins University Applied Physics Laboratory (JHU/APL), where he is responsible for the oversight and coordination of all laboratory technical programs. Prior to his current assignment, Dr. Kalbaugh was head of the Power Projection Systems Department, where he was responsible for programs in strike warfare, defense communications, and information operations. His background is in tactical missile and precision strike systems. He joined JHU/APL in 1969 and was involved in the development of the Tomahawk cruise missile system at its inception. In addition to his supervisory and management duties, Dr. Kalbaugh has taught for more than a decade in JHU's Whiting School of Engineering. He has served on numerous scientific boards and advisory committees, including participation in tasks for the Undersecretary of Defense for Acquisition and for the program executive officer for Theater Air Defense. Dr. Kalbaugh is a member of the NRC's Naval Studies Board.

Carl E. Landwehr is program director of the newly established Trusted Computing Program at the National Science Foundation, where his research interests include information security and dependable systems. He is currently on assignment from the University of Maryland's Institute for Systems Research. Prior to this assignment he was a senior fellow in the Center for Information Technology and Telecommunications at Mitretek. Before joining Mitretek, Dr. Landwehr headed the Computer Security Section of the Center for High Assurance Computer Systems at the Naval Research Laboratory (NRL), where he led a variety of research projects to advance technologies of computer security and high-assurance systems. He has served on numerous scientific boards and advisory committees, including editorial boards for the Institute of Electrical and Electronics Engineers' (IEEE's) *Transactions on Software Engineering* and for the *Journal of Computer Security* and the *High Integrity Systems Journal*. He received a B.S. degree in engineering and applied science from Yale University and M.S. and Ph.D. degrees in computer and communication sciences from the University of Michigan.

James R. Luyten is the executive vice president and director of research at Woods Hole Oceanographic Institution. During his 31 years at Woods Hole, Dr. Luyten's research interests have included the structure and dynamics of the general North Atlantic circulation and observations and instrumentation designed to understand the underlying processes of ocean currents, particularly long-period equatorial variability and its relation to the mean circulation. Many of these studies have involved the use of semiautonomous and fully autonomous undersea vehicles as principal observation platforms. Dr. Luyten has participated in 7 major field programs and 18 oceanographic cruises, serving as chief scientist on 10 occasions. He has served on numerous scientific boards and advisory committees, including as chair of a Naval Research Advisory Committee examining the role of unmanned vehicles in mine countermeasures. Dr. Luyten completed his A.B. degree at Reed College and his M.A. and Ph.D. degrees at Harvard University.

Carl Mikeman is the advanced systems program manager and electro-optical sensor specialist at the Northrop Grumman Ryan Aeronautical Center. Mr. Mikeman has more than 30 years' experience in the technical and management aspects of system design and development related to electro-optical imaging systems, sensors, and seekers, with emphasis on UAVs and other airborne platforms, including field and flight testing and evaluation. He is currently responsible for evaluating sensor and seeker payloads and integrating them into unpiloted aircraft. Mr. Mikeman also has primary responsibility at the Ryan Aeronautical Center for the development of UAVs for Ryan's DARPA/U.S. Army Future Combat Systems Program, and he is program manager for the development of Northrop Grumman's UAV control console.

John B. (Brad) Mooney, Jr., Rear Admiral, USN (Ret.), retired from the U.S. Navy in 1987 after more than 34 years of professional, commissioned officer experience, including a total of six commands both at sea and ashore and various, diverse staff assignments in the fields of management, research, education, training, manpower planning, and very deep ocean operations. During his Navy career, Admiral Mooney's last active-duty positions were as oceanographer for the Navy and Navy deputy of the National Oceanic and Atmospheric Administration from 1981 to 1983 and as Chief of Naval Research from 1983 to 1987. In addition, he had directed all Navy training and education activities and manpower requirements planning for the Chief of Naval Operations from 1978 to 1981. After retiring from the Navy, Admiral Mooney consulted and was president of the Harbor Branch Oceanographic Institution from 1989 to 1992. Today he is an independent consultant to ocean engineering and research managers. A member of the National Academy of Engineering, Admiral Mooney has served on numerous scientific boards and advisory committees. He is past chair of the NRC's Marine Board and the NRC Committee on Undersea Vehicles. He received a B.S. from the U.S. Naval Academy.

Stewart D. Personick is an independent consultant, having recently retired as the E. Warren Colehower Chair Professor of Telecommunications and director of the Center for Telecommunications and Information Networking at Drexel University. Dr. Personick, a member of the National Academy of Engineering, has an extensive background in telecommunications, networking, and networking/network-based applications security and in optical communications technology and applications. As the first director of Drexel's Center for Telecommunications and Information Networking, he created four initial programs: Networks That Work, Trustworthy Networks, Next Generation Wireless, and Optical Networking. Dr. Personick is retired from Bell Communications Research, Inc. (Bellcore), where he served as vice president of information networking research. He is a current member of the NRC Board on Army Science and Technology and a member of the board of directors of Optical Communications Products, Inc.

Nils R. Sandell, Jr., is vice president and general manager of BAE Systems Advanced Information Technologies. Dr. Sandell has an extensive background in military command, control, intelligence, surveillance, and reconnaissance systems and technologies. His areas of expertise include automatic target recognition, sensor fusion, sensor resource management, and battle management/command, control, and communications. He is a former associate professor at the Massachusetts Institute of Technology, where he lectured in the areas of estimation and control theory, stochastic processes, and computer systems. Dr. Sandell has served on numerous scientific boards and advisory committees, such as the 2001 Defense Science Board study on precision weapons targeting. Dr. Sandell is a member of the Naval Studies Board.

Howard E. Shrobe is principal research scientist at MIT's Artificial Intelligence Laboratory, where his research interests are in intelligent systems, knowledge-based software development, evolutionary design of complex software, and information survivability. From 1994 to 1997, Dr. Shrobe served as assistant director and chief scientist for DARPA's Information Technology Office, where he was responsible for the two programs Evolutionary Design of Complex Software and Information Survivability. Dr. Shrobe has served on numerous scientific boards and advisory committees, including the NRC Committee for the Review of ONR's Technical Visions for UCAVs.

James M. Sinnett, an independent consultant, recently retired as vice president of technology at the Boeing Company, where he served as Boeing's senior spokesman on technology matters. Prior to that position, he served as the corporate vice president of technology for McDonnell Douglas. He joined McDonnell as a test engineer and was involved with the development of the propulsion systems for Projects Mercury and Gemini. He has since worked on a number of advanced concept development programs for hypersonic aircraft, advanced subsonic fighters/interceptors, control configured vehicles, and high-acceleration cockpits. Mr. Sinnett serves on a number of scientific boards and advisory committees and is a member of the NRC's Naval Studies Board.

Marilyn J. Smith is associate professor of aerospace engineering at the Georgia Institute of Technology. Dr. Smith has extensive experience with fixed- and rotary-wing aeroelastic problems. Her research interests include unsteady computational aerodynamics, computational aeroelasticity, and the integrated multidisciplinary areas of design of aeroelastic configurations and acoustic/fluid/structure interactions. She is a member of the American Helicopter Society (AHS) and has served on the National Technical Committee on Fluid Dynamics/Aerodynamics for both the AHS and the American Institute of Aeronautics and Astronautics.

Charles E. Thorpe is director of the Carnegie Mellon University's Robotic Institute in the School of Computer Science and a founder of the institute's master's degree program. Since 1984, he has worked on the development of outdoor robotic vehicles, focusing on computer vision, planning, and architectures for these machines. Dr. Thorpe and his naval laboratories research group have built a series of 11 robotic cars, trucks, and buses for military and civilian research. He and his team have pioneered new methods in stereo vision, laser rangefinding, three-dimensional terrain modeling, neural networks for perception, route planning, driver-performance modeling, traffic simulation, teleoperation, vehicle control on rough terrain, and system architectures. Dr. Thorpe has also been involved in the development of automated helicopters, walking robots, and robots that operate under water. He received his doctoral degree in computer science from Carnegie Mellon University in 1984 and his undergraduate degree in natural science from North Park College in Chicago in 1979. He is a fellow of the American Association for Artificial Intelligence.

David Whelan is vice president-general manager and deputy to the president of Boeing Phantom Works, Boeing's central research and development organization. Prior to joining Boeing in 2001, Dr. Whelan was director of the Tactical Technology Office at DARPA, where he led the development of enabling technologies, such as unmanned vehicles and space-based moving target indicator radar systems. Prior to his position with DARPA, Dr. Whelan held several positions of increasing responsibility with Hughes Aircraft. His experience in high-technology development also includes roles as a research physicist for the Lawrence Livermore National Laboratory and as one of four lead engineers assigned for the design and development of the B-2 Stealth Bomber Program at Northrop Grumman. Dr. Whelan earned his Ph.D. and M.A. degrees in physics from the University of California at Los Angeles and his bachelor's degree in physics from the University of California at San Diego.

Brian H. Wilcox is the supervisor of the Robotic Vehicles Group at the National Aeronautics and Space Administration's Jet Propulsion Laboratory (NASA JPL). In the summer of 1997, the Robotic Vehicles Group was responsible for the control and navigation of the Sojourner Rover, which explored part of Mars. His group at NASA JPL was responsible for similar activities for the Mars Exploration Rover exploring Mars in 2004 and 2005. Mr. Wilcox's research interests include electronics and navigation sensors; control software, including hazard detection and avoidance; and mission operations. Mr. Wilcox was personally responsible for conceiving and developing the stereo camera and laser ranging system used on the Sojourner rover. He received the NASA Exceptional Engineering Achievement Medal in 1992 and the JPL Award for Excellence in 1999 and 2001. He holds six U.S. patents in the area of robotics. Mr. Wilcox received an M.S. in electrical engineering from the University of Southern California and a B.S. in physics and a B.A. in mathematics from the University of California at Santa Barbara.

Staff

Charles F. Draper is acting director at the National Research Council's Naval Studies Board. He joined the National Research Council in 1997 as program officer, then senior program officer, with the Naval Studies Board and in 2003 became associate director. During his tenure with the Naval Studies Board, Dr. Draper has served as the responsible staff officer on a wide range of topics aimed at helping the Department of the Navy with its scientific, technical, and strategic planning. His recent efforts include topics on network-centric operations, theater missile defense, mine warfare, and nonlethal weapons. Prior to joining the Naval Studies Board, he was the lead mechanical engineer at Sensytech, Inc. (formerly S.T. Research Corporation), where he provided technical and program management support for satellite Earth station and small-satellite design. He received his Ph.D. in mechanical engineering from Vanderbilt University in 1995; his doctoral research was conducted at the Naval Research Laboratory (NRL), where he used an atomic force microscope to measure the nanomechanical properties of thin-film materials. In parallel with his graduate student duties, Dr. Draper was a mechanical engineer with Geo-Centers, Inc., working on-site at NRL on the development of an underwater x-ray backscattering tomography system used for the nondestructive evaluation of U.S. Navy sonar domes on surface ships.

Arul Mozhi is senior program officer at the National Research Council's Naval Studies Board and served as senior program officer at the NRC's Board on Manufacturing and Engineering Design and National Materials Advisory Board. Prior to joining the NRC in 1999, Dr. Mozhi was senior scientist and program manager at UTRON, Inc., a high-tech company in the Washington, D.C., area, working on pulsed electrical and chemical energy technologies applied to materials processing. From 1989 to 1996, Dr. Mozhi was a senior engineer and task leader at Roy F. Weston, Inc., a leading environmental consulting company working on long-term nuclear materials behavior and systems engineering related to nuclear waste transport, storage, and disposal in support of the U.S. Department of Energy. Before 1989 he was a materials scientist at Marko Materials, Inc., a high-tech firm in the Boston area, working on rapidly solidified materials. He received his M.S. and Ph.D. degrees (the latter in 1986) in materials engineering from the Ohio State University and then served as a postdoctoral research associate there. He received his B.S. in metallurgical engineering from the Indian Institute of Technology in 1982.

B

Some Physics-Based Constraints on Autonomous Vehicles: Scaling, Energy, Sensing, and Communications

The purpose of this appendix is to provide a technical discussion of autonomous vehicle (AV) scaling, energy, sensing, communications, and related topics. Although these areas are touched upon in this report's chapters on unmanned aerial vehicles (UAVs), unmanned surface vehicles/unmanned undersea vehicles (USVs/UUVs), and unmanned ground vehicles (UGVs)—that is, in Chapters 4, 5, and 6, respectively—the details and physics-based constraints are discussed at greater length in this appendix.

RANGE AND ENDURANCE

For most missions of interest, the range and endurance of an autonomous vehicle are crucial parameters that affect the suitability of that vehicle for any particular mission. The cost of the system that can accomplish a mission grows with requirements for increasing range and endurance. It is important to understand how basic physics determines the variations in size, mass, and cost of autonomous systems in response to variations in the needed range and endurance for individual missions.

The principal factor affecting range and endurance is energy storage. For an atmospheric or underwater vehicle, the basic physics is that the drag force is proportional to V^2, where V is the velocity of the vehicle. The drag power is proportional to V^3. Both vary with the surface area, or with R^2, where R is the radius of the vehicle's fuselage or hull. The amount of energy storage available in the vehicle is proportional to the volume, and so is proportional to R^3. So a simplistic, back-of-the-envelope estimate of the endurance time t of a vehicle that maintains a velocity V is $t = kR/\rho V^3$, and the total distance covered is $S = Vt = kR/\rho V^2$. Here, k is a constant that depends on the type of energy storage and on geometric factors relating to how streamlined the vehicle is. For vehicles that derive their energy from chemical storage and which are streamlined with the usual 12:1 length-to-diameter aspect ratio appropriate for conventional high-strength materials, the value of k can range up to about 10^{11} in metric units. This factor k can vary by a modest amount, depending on the specific chemicals used for energy storage, the fraction of total volume devoted to fuel, and so on. The Greek letter "rho" (ρ) is the density of the medium that the vehicle moves through (1,025 kg/m^3 for seawater and 1.29 kg/m^3 for air at sea level).

Thus, both range and endurance are expected to be roughly proportional to the scale of the vehicle. Smaller vehicles can be used if one is willing to make a proportionate sacrifice in range and endurance. The mass of the vehicle, which generally determines the cost and the difficulty of handling logistics, is proportional to R^3. So range and endurance are found to be proportional to $M^{1/3}$, where M is the gross (fully loaded) mass of the vehicle. Furthermore, range varies inversely with V^2, and endurance varies inversely with V^3. Thus, it is very important that the vehicle move only as fast as necessary to accomplish its mission, but no faster.

For endurance, a lower bound on velocity is primarily determined by the fluid disturbances that the vehicle must fight. In both atmospheric and underwater vehicles, the natural disturbances with which the vehicle must contend are driven by solar power. The fluid disturbances in the atmosphere and under water rarely exceed the power densities ($\frac{1}{2}\rho V^3$) of the incident solar power flux (1,350 W/m^2). Under water, this means that characteristic currents are 1.4 m/s (2.7 knots). In the atmosphere, because the density of air is so much lower, the velocity of typical disturbances is higher, about 14 m/s (27 knots) at sea level and 36 m/s (70 knots) at 18 km altitude (59,000 ft). Most autonomous vehicles designed for long endurance cruise at a speed that ranges from 1.3 to 5 times faster than these disturbances, so that they have sufficient command authority to loiter over a stationary point and to reach new targets of interest despite the occasional flow that exceeds the solar power flux. One side effect of the solar origin of these disturbances is that an infinite-endurance solar-powered aircraft is barely possible, since the wing area can collect power at about the same rate at which a minimal vehicle expends it.[1]

The simple analysis here shows that the endurance of a vehicle varies inversely with ρV^3, which itself is just a fixed multiple of the solar constant, and so the endurance of a vehicle that has a fixed velocity margin over the natural

[1]See, for example, the Web site <http://www.aerovironment.com/area-aircraft/unmanned.html>. Last accessed on April 1, 2004.

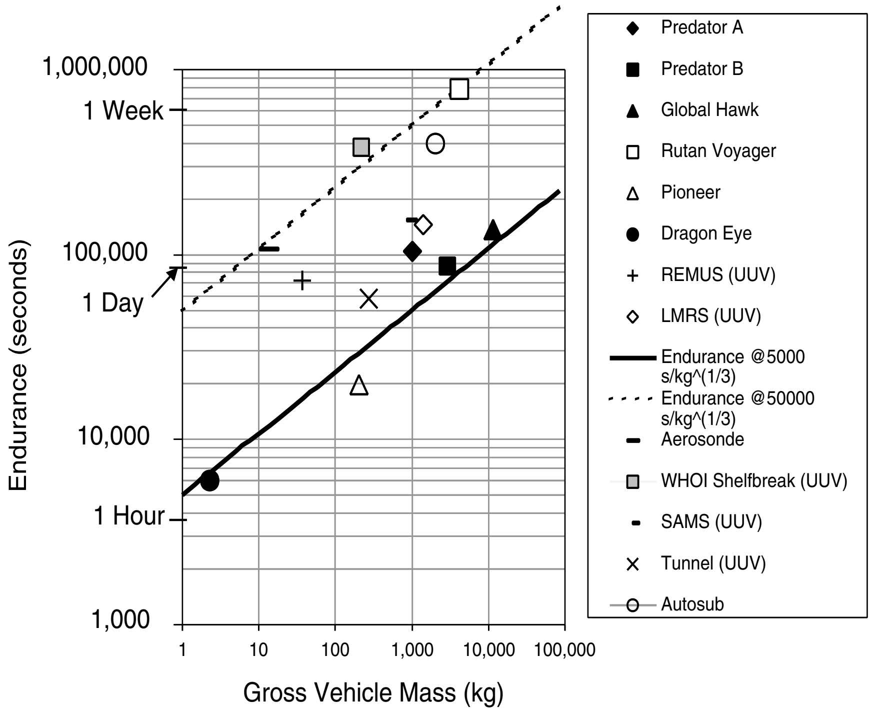

FIGURE B.1 Endurance versus mass for typical vehicles. NOTE: A list of acronyms is provided in Appendix D.

disturbances is found to be approximately independent of the density of the fluid that it moves through. This means that unmanned aerial vehicles and unmanned underwater vehicles will have the same endurance-mass relationship. Shown in Figure B.1 is a plot of gross vehicle mass versus endurance for several vehicles, along with two curves for constant endurance per $kg^{1/3}$. All the UAVs and UUVs lie within the same band of constant endurance per $kg^{1/3}$, as predicted by this simple model, over a range of four orders of magnitude.

One example near the extreme in Figure B.1 is the Rutan Voyager, which flew nonstop around the world without refueling; that flight took place in December 1986 over a period of 9 days, with two pilots onboard. The Rutan Voyager was built using the most advanced composite materials and methods, and it demonstrates that significant advances in endurance are possible, even though it is far too fragile a craft for naval operations. If current research (e.g., in carbon nanotubes) is successful in creating useful materials with a strength-to-weight ratio up to two orders of magnitude higher than that of conventional materials, it may be possible to build vehicles that equal or exceed the performance of the Rutan Voyager and yet are rugged enough for naval operations.

All of the vehicles listed in Figure B.1 are highly streamlined, and for aircraft they all use a high-aspect-ratio, high-lift-to-drag-ratio wing. If other considerations force the vehicle design away from this approach, the endurance can be expected to suffer accordingly. It is perhaps worth noting that aircraft normally carry only one of the two chemical reactants needed for energy storage and ingest the needed oxygen from the air. This makes chemical energy storage for aircraft somewhat more efficient than that for underwater vehicles, which generally carry both components of the chemical reaction. But an aircraft must lift its own weight, and so it requires a large wing and its associated drag, while the UUV is neutrally buoyant. These two effects roughly cancel one another.

It is perhaps worth discussing briefly the possibility that something other than chemical energy might be used. Nuclear power has its own scaling difficulties, since a critical mass of fissionable material is of a fixed size, not to mention the severe political, environmental, and practical handling problems once the vehicle structure is thoroughly bombarded with neutrons. Radioisotope thermal power sources currently have specific power densities of only ~5 W/kg, compared with chemical engines, which have useful outputs of 1 to 2 kW/kg. So the power density of radioisotope power is too low for aircraft but might work for very slow submersibles. An interesting possibility is beamed power, involving laser or microwave energy directed at the vehicle from a remote source to completely break all of these scaling relations. And lastly, as previously mentioned, infinite-endurance solar-powered aircraft are possible (they store extra energy in the daytime for use at night or simply glide all night). At this time, none of these alternative energy sources is highly attractive for naval operations.

While endurance is approximately the same for UAVs and UUVs of the same mass, the range of the vehicles is radically different. Since ρV^3 is roughly constant for all of these vehicles, V is proportional to $\rho^{1/3}$. This means that the speed of a low-altitude UAV will be about 9 times faster than that of a UUV, and a high-altitude UAV will be at least 25 times faster than a UUV. So over the same endurance time, a UAV will cover much more distance than can be covered by a UUV of the same mass, as one would expect intuitively. The fact that range and endurance suffer so badly from increases in velocity (inversely with V^2 and V^3, respectively) makes it unattractive to have the vehicles "sprint" to their operational stations. This logic suggests air deployment of UUVs when the mission calls for them to be a long way from the fleet, perhaps using UAVs designed for this purpose.

In-flight refueling of UAVs and UUVs is also attractive: small, low-signature vehicles will have limited endurance, but they could rendezvous with a much larger "tanker," which has significant endurance. Since the tanker would not carry the expensive sensor package, it could be much cheaper than the smaller vehicles. Unfortunately, the existing fleets of KC-130 aerial tankers operated by the Air Force have a minimum speed that is much too great for UAVs to match, given the scaling issues addressed here. Some C-130 tankers configured for in-flight refueling of helicopters may be suitable for refueling UAVs.

A key point here is that the Navy should not try to make UAVs that are compatible with the existing jet-refueling tankers, since the high-speed requirement is so contrary to the need for long endurance. And it may not be practical, at least initially, to build a new fleet of tankers specifically for UAVs. It is perhaps most important to deploy a system that is capable, yet highly affordable in all stages of deployment. Deploying "Predator-class" UAVs and torpedo-tube-compatible UUVs from the fleet will accomplish most missions at low cost and low risk without in-flight refueling and without onerously frequent launch and recovery. In October 1996, the Predator Marinization Feasibility Study, conducted by the Program Executive Office, Cruise Missiles and Unmanned Aerial Vehicles (PEO(CU)) under the direction of Commander Kurt Engel, USN, concluded, "The assessment finds that the marinization of the Predator-A system to takeoff and land on CV/LH [aircraft carrier/amphibious assault] class ships is feasible with moderate costs." There were a number of issues, including those of using a heavy-fuel engine versus avgas, the wind over deck margin, and problematic flying qualities in the aft deck burble, but the study concluded that the issues were resolvable.

The endurance of the marinized version of the Predator was estimated at 22 hours. It would seem that a redesigned, perhaps slightly larger vehicle could be made so that it could launch at the beginning of a flight-deck operations shift on one day and not be recovered until the end of the shift on the following day, greatly increasing the total number of vehicles that the fleet can sustain. The cost of these UAVs could perhaps be made significantly less than the cost of shooting them down, especially if each of them carried suitable suppression of enemy air defense (SEAD) implements. With clever design it should be possible to pack multiple Predator-class UAVs in the space of a single manned aircraft belowdecks, given that a combat aircraft has a mass of more than 30 tons at launch, while each UAV is only 1 or 2 tons. For example, the UAVs could be designed with their wings hinged on each side about halfway out, and then the whole wing would pivot to line up with the fuselage so that it all fit in a "cigar tube" whose length is about half of the UAV's deployed wingspan (the same configuration as that of the small Finder UAV developed by the Naval Research Laboratory; Figure B.2). The 18 m length of a manned aircraft is more than twice the length of a Predator-class vehicle packed this way, so it seems possible to have a $3 \times 5 \times 2$ array (30 total) of UAVs stowed in the same space as a current combat aircraft. Once combat operations begin, these "boxed and stacked" vehicles will necessarily come out and stay out "on their tires" for the duration of operations. But if they have an endurance of 2 days, then during combat opera-

FIGURE B.2 The Finder unmanned aerial vehicle developed by the Naval Research Laboratory has a folding and pivoting wing to stow in a "cigar-tube" shape. SOURCE: Office of the Secretary of Defense. 2002. *Unmanned Aerial Vehicles Roadmap 2002-2027*, Department of Defense, Washington, D.C., December.

tions, at most half are onboard at any time. If each UAV has a highwing that pivots over the fuselage, they could be parked with the fuselages almost side by side and still be on their tires (e.g., each on a 9 × 1.7 m spot). Each unpacked UAV would take perhaps three times the "spot factor" of the stacked units, but half of them would be in the air, so instead of having a ratio of 30 per current manned vehicle, one might effectively have 20.

Where does this very simplistic analysis fail to capture the essential issues? For very small vehicles, the dimensionless Reynolds number that characterizes the fluid flow around a body gets outside the range in which the drag coefficient is roughly constant, as assumed. To date, human-built vehicles at extremely small scales have had even lower range and endurance than this simple analysis would indicate, because of this effect. However, the animal world gives numerous examples showing that this need not be so. For example, a well-fed housefly has an endurance of about an hour, which is possible only because the wing of the fly is able to take remarkable advantage of "swimming in its own vortices" in a manner not yet fully understood. For larger aircraft, the simple model used here predicts that the range and endurance can be increased without bound by making the vehicle large enough. This is not quite true. To understand further, consider that most aircraft have a lift-to-drag ratio (L/D) between 10 and 40. If all of the lift is used to carry fuel of mass M, then $L = Mg$, where g is the acceleration of gravity. The drag D times the velocity V is the mechanical power needed to sustain flight, which is the energy E contained by the fuel divided by the endurance t, so $DV = E/t$. But the best fuels have a specific energy E/M of about 50 MJ/kg, so $L/D = Mg/(E/Vt) = (M/E)/(Vt)$ or $Vt = (L/D)(E/M)/g$. The product of velocity times endurance is range; thus, the maximum possible range of a vehicle, at any scale, is roughly the lift-to-drag ratio of the airframe times the specific energy of the fuel divided by the acceleration of Earth's gravity. For L/D = 10, this maximum range turns out to be 50,000 km, or slightly more than the circumference of Earth.

This result means that the feat of the Rutan Voyager in flying around the world without refueling was not something that could be easily achieved simply by making a bigger vehicle. Instead, it was required that the product of the lift-to-drag ratio and the overall power efficiency of the propulsion system had to be about 10, which is very difficult to achieve at any scale. Once again this analysis is somewhat simplistic, in the sense that, as fuel burns off and the vehicle becomes lighter, the angle of attack of the airfoil can be reduced to lower the drag. This effect has been neglected; in principle it could be used (in the extreme case by staging away unneeded surfaces as fuel is spent, much like a rocket is staged) to give endurance limited only by the strength-to-weight ratio of the structural materials. In normal practice the maximum endurance of a vehicle is proportional to the product of the lift-to-drag ratio, the effective specific energy of the fuel (after accounting for the conversion efficiency of the propulsion system), and (again much like a rocket) the logarithm of the ratio of the wet mass to the dry mass of the aircraft (i.e., with and without fuel, respectively). Note that this formula for range does not involve velocity, since the airframe can be designed to have the needed lift and a good lift-to-drag ratio at any reasonable, preselected subsonic speed and altitude. However, velocity does affect endurance. Since the endurance time is the range divided by the velocity, the loiter time of such a vehicle is inverse with V. Once again, high velocity implies lower endurance, as concluded previously.

The transition region between a UAV whose endurance is proportional to $M^{1/3}$ (as is the original simplistic analysis) and where it levels off independent of M (this latter analysis involving L/D and E/M) occurs when all of the fuel fits into the wings, so that the vehicle has no fuselage. The longest-endurance, greatest-range systems would be expected to be large, flying wings. For a small vehicle this is not possible, because the volume of a small, thin wing is too low to achieve normal wing loading only with the fuel that fits inside. (Normal wing loading is about 25 kg/m^2 for a sailplane—3 times that for a civil aviation aircraft, 9 times that for the Global Hawk, or 27 times that for a modern fighter aircraft.) Even with the light wing loading of a sailplane, the average wing thickness would need to be about 3 cm to hold all of the fuel. A wing chord (the distance from the leading to the trailing edge) is typically about 10 times the wing thickness, and, for a high L/D, the wingspan is often 20 or 30 times the chord. Thus, the smallest maximal-endurance flying wing possible with chemical fuels has a wingspan of about 10 m, and in practice it might be 2 or 3 times that big. Smaller vehicles must have a fuselage to hold the fuel that does not fit in the wing, and the drag of this fuselage follows the initial simplistic scaling laws used here.

In summary, a simple scaling analysis points out that vehicles with reasonable endurance tend to be moderately large, but are still much smaller than corresponding manned vehicles. Very small vehicles will have very limited range and endurance, as one would expect intuitively. Because of the strong dependence of velocity on range and endurance, it would be very helpful to base the vehicle close to the theater of operations (e.g., on ships), since either it could take the vehicle a very long time to get there on its own, or else it would need to give up a large fraction of its endurance to sprint to the theater. (Actually, for the vehicles in consideration, the dimensionless Reynolds number that characterizes the fluid flow varies from $\sim 10^4$ to $\sim 10^7$ between the smallest, slowest vehicles and the largest, fastest vehicles. There is a significant drop in drag coefficient over that range, so endurance is observed to vary less rapidly than with the inverse cube of the velocity between vehicles optimized at each design point. Empirically, this exponent is found to be slightly less than 2, which is still high enough to impose a significant penalty for high speed.) In any event, both UAVs and UUVs will need to have a mass of 1 ton or a few tons, if only to limit the launch and recovery frequency to an acceptable level, except for those vehicles used for extremely short-duration or short-range missions such as for hand-deployed units used by Special Operations Forces or frontline troops.

Attempts to combine long endurance, substantial payload, high speed, and stealth (e.g., poor aerodynamics) in a single vehicle face tremendous obstacles. The basic physics suggests a separation of functions, using a slow, high-altitude UAV to get the targeting information to call in strikes using other forms of attack, or having a small missile or two on the "big-wing" UAV for really time-critical targets. Presumably most or all combat (as opposed to intelligence, surveillance, and reconnaissance (ISR)) aircraft will slowly be replaced with UAVs as the technology advances. These combat UAVs will need to be much more massive than the ISR UAVs in order to achieve all of the endurance, payload, speed, and stealth requirements. The current uninhabited combat air vehicle-Navy (UCAV-N) under development is an example of this larger size, although it is still smaller than a manned aircraft designed for the same mission—two of the UCAV-Ns fit in the space needed for a normal carrier-based combat aircraft.

LAUNCH AND RECOVERY

Launch and recovery of aircraft from ships constitute a major issue. For example, the launch catapult and landing arrestor on aircraft carriers are designed for vehicles at least an order of magnitude heavier than the UAVs considered here. Fortunately, long-endurance UAVs fly slowly, so they can take off and land at speeds that barely exceed the speed of the fleet when it is under way. Thus, it should be possible to arrange a separate launch-and-recovery apparatus that would only need to deliver or absorb about 1 percent or less of the energy of the traditional systems for these ISR UAVs, if such an apparatus is needed at all. (Both C-130 transport aircraft and U-2 reconnaissance jets have successfully landed and taken off from aircraft carriers without either launch catapults or landing arrestors.[2]) The combat UAVs, as mentioned, will be comparable in mass to current manned aircraft and therefore should be able to use the same launch-and-recovery systems. (Being unmanned, these UAVs can take the higher acceleration that being lighter implies.) Carrier-deck operations currently require that UAVs maneuver and respond in the same way as manned aircraft to radio commands, hand signals, and so on. This requirement suggests that initially each UAV needs to be controlled by a human pilot via a direct, high-bandwidth, low-latency, "telepresence-style" data link during launch and recovery operations. Having such a control mode also may continue to be required for operation with the current civil air-traffic-control system as is needed for many routine transit operations and training purposes.

Having a moderately large vehicle has other advantages beyond endurance. At the very least, a larger vehicle is able to devote more mass and power to sensing and communications than a small vehicle can. Also, basic physics dictates that sensor angular resolution is inversely proportional to the sensor aperture. For wavelengths and resolutions of interest (e.g., a few-centimeter resolution at several tens of kilometers of slant range using visible imagery or synthetic aperture radar (SAR)), the needed apertures tend to be a significant fraction of a meter. So, serendipitously, the radius of the vehicle should be about the size needed for adequate endurance, just to get the aperture sizes needed for reasonable standoff from the target. The vehicle could be moved closer, of course, but then it would be much more vulnerable, have much less sensor coverage, and be subject to the weather. A similar scaling argument shows that it takes a fairly large and sophisticated system to destroy a hard-to-see, low-power aircraft at ~20 km altitude—the argument based both on the energy needed for the vehicle to get up that high quickly and on the illumination power and resolution needed for the

[2]For the history of the C-130, see the Web site <http://www.aerospaceweb.org/question/history/q0097.shtml>; and for the history of the U-2, see <http://www.aerospaceweb.org/question/history/q0050.shtml>. Last accessed on April 1, 2004.

sensor to see the target. This large, sophisticated system will itself be vulnerable and will have a cost comparable to that of the UAV. Similar arguments about sensor apertures apply to submersibles. Thus, one finds that aerial or underwater autonomous vehicles having enough range and endurance to avoid nearly continuous launch-and-recovery operations will have a mass of 1 ton or a few tons, will move relatively slowly, will be based relatively close to the target area, and will be able to have superb sensor resolution and relative immunity from attack, especially when viewed in terms of the cost ratio compared with potential countermeasures.

COMMUNICATIONS

Another key issue for autonomous vehicles is communications. Sensors on an approximately 1 ton autonomous aircraft are capable of generating huge amounts of information (~10^{17} bits per second), based on diffraction-limited resolution and Poisson-limited shot noise, taking full advantage of the large number of thermal and visible photons that flood the environment. Real sensor systems today only deliver a very small fraction of this theoretical limit, but still they frequently overwhelm the available communications bandwidth. However, the basic physics of communications between UAVs, surface combat units, satellites, and ships suggests that it may be possible to return essentially all of the data collected by UAVs.

Moderately large UAVs, as described above, flying at relatively high altitude (to obtain greater sensor coverage, all-weather performance, and relative immunity from attack) generally have a line of sight to other UAVs, to satellites, and often to surface or low-altitude assets as well as to ships at sea. Focused beams of radio-frequency (RF) power can be transmitted between these systems, with modest frequency allocation limitations and very little signature. In particular, RF communications using focused beams between similar UAVs at ranges up to 550 km per leg (the "clear air" horizon limit at 18 km altitude) can carry huge amounts of information. The pointing, tracking, and vehicle-position and attitude knowledge requirements for such communications are not greater than those needed for the basic sensing and targeting functions of the vehicle. (It is especially crucial to know the vehicle attitude precisely for targeting, a fact that has been overlooked in some prior systems. One way to do this for high-altitude UAVs is with a star tracker, which can provide a low-cost, low-mass way to get precise orientation at high altitude, even in the daytime, since the bright stars are visible in the dark sky.)

The Office of the Secretary of Defense is proceeding vigorously with the Global Information Grid (GIG), which seems well tailored to the needs of UAVs and allows transport of large amounts of information from these vehicles to the fleet, to the continental United States (CONUS), or to Marines on the frontlines,

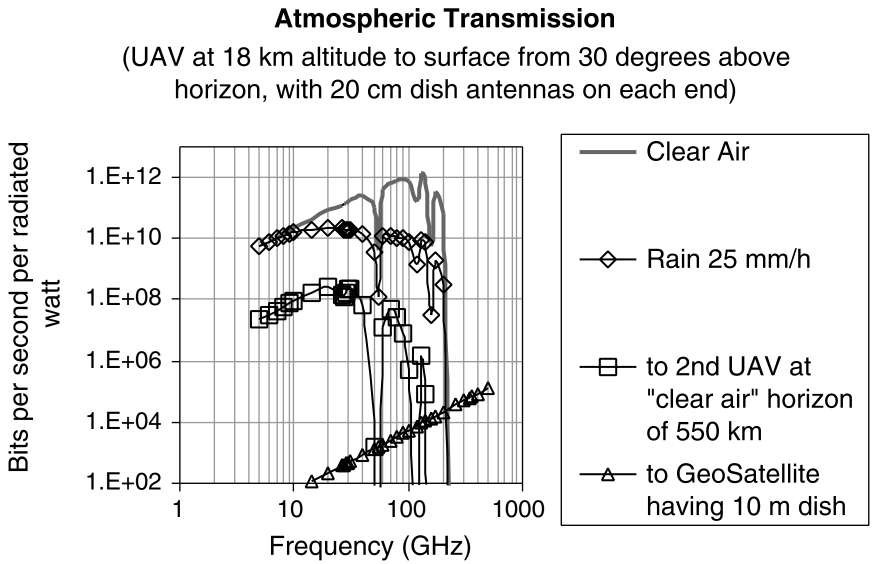

FIGURE B.3 Communications between unmanned aerial vehicles (UAVs) and the ground, other UAVs, and a geosynchronous satellite.

at or near the limits imposed by fundamental physics. As this system matures and deploys, the currently large gap between the ability of UAV sensors to create data and the ability of the communications network to deliver them should disappear. It is important to note that, while the GIG architecture includes satellite communications as part of the grid, this may not be the most important part relevant to UAV systems. Instead, a rich network of point-to-point RF communications between dozens or hundreds of unmanned vehicles will offer tremendous volumes of data through a relatively robust system. The GIG architecture seems well crafted to manage the complexity and dynamic routing requirements of this future environment.

Many presentation packages from all of the military Services depict a future scenario with a densely connected grid of communications over the battlespace. However, it is not clear that any of the Services is making detailed plans or taking responsibility for making this communications grid a reality. It may be that UAVs, and naval UAVs in particular, are especially well suited for making this essential battlespace infrastructure possible. Figure B.3 shows a plot of the theoretical maximum data rate per transmitted watt from a UAV at 18 km altitude to the ground, under various weather conditions. It is assumed that each end of the link uses a 20 cm (8 in.) diameter parabolic dish antenna. Note that, with the exception of the oxygen absorption band between 50 and 60 GHz, it is possible to transmit over 10 gigabits per second (Gbps) per watt at any frequency from about 8 GHz to over 100 GHz, even through heavy rain (1 inch per hour). Also plotted is the maximum data rate between two UAVs at the "clear-air" horizon distance of 550 km (maintaining the line of sight above 12 km so as to be above essentially all weather). Real communications systems will have a performance less than this theoretical maximum, of course, but even with existing technology the actual performance will be close to these curves. To be immune from jamming, it is generally assumed that between 100 and 1,000 times as much energy per bit is required above this theoretical minimum. Because the sidelobes of the antenna pattern are so much smaller at high frequencies, less jamming margin is needed there, and the link is much more clandestine. Thus, one might speculate that it is possible to build a robust communications link at almost 100 GHz that communicates almost 100 megabits per second (Mbps) per watt between the UAV network and small mobile units on the ground. Given that a typical cellular phone transmits up to 3 W, this level of performance seems good enough for even small units of Marines to obtain a real-time picture of events from the UAVs.

In Figure B.3 it is assumed that the UAV is 30 degrees above the horizon of the unit on the ground. To have one UAV at least 30 degrees above the horizon for every spot in a 1000 × 1000 km battlespace would require about 730 UAVs, which could be hosted by a single aircraft carrier if they had a mass of only 1 ton each and had at least 2 days' endurance, as described previously. Since the most useful information for the unit on the ground probably comes from the UAV in direct line of sight, there may not be a tremendous load on the network transmitting between UAVs in support of ground operations. Most units would request ISR data from "their" UAV overhead. It does not seem difficult to endow each UAV with a half-dozen or more 8 in. dishes to talk to people on the ground for this purpose. As an "antenna farm," these UAVs would not be especially stealthy, but they could be fairly small and fairly cheap. The same basic airframe with an electro-optical infrared (EO/IR) sensor (needed by the pilot anyway) and communications package, with a payload bay that can accommodate a SAR, extra fuel tanks, a couple of joint direct attack munitions (JDAMs), or other payloads, can be imagined.

Also plotted in Figure B.3 is the corresponding data rate per watt for a UAV transmitting to a geosynchronous satellite, as is done by the Global Hawk and the Predator. Note that the data rate per watt is generally at least a million times worse than it is between the UAVs and the ground, despite the assumption made here that the satellite uses a large, 10 m (33 ft) dish antenna. This severe performance penalty comes from the extreme distance to geosynchronous orbit, with the attendant inverse-square losses. The bulbous nose of the Global Hawk and the Predator come from the need to use a very large antenna for satellite communications, which substantially affects the aircraft's drag, mass, complexity, cost, and endurance. It is not clear that many or any of the UAVs actually need or benefit from satellite communications.

An additional element of the communications system is the need for an omnidirectional, low-bandwidth link for making requests for access to the precisely pointed antenna system. Since each unit will know its own IMU (inertial measurement unit)-augmented Global Positioning System (GPS) location, only a small amount of data needs to be transmitted to allow the two ends of the link to align for the high-bandwidth communications session. Cellular-phone-class systems should be capable of performing this function for ground units wishing to connect to the data network, while UAVs at long range from each other can get the location of new UAVs entering the grid using low-bandwidth links from the fleet or from satellites. The low-bandwidth omnidirectional system will presumably operate at very high frequency/ultrahigh frequency (VHF/UHF), and thus also allow communications of modest amounts of data to units under forest canopies and in other heavily cluttered regions.

It seems that the mass versus endurance argument makes the Navy the logical home for this UAV communications system. A fleet-based system is going to be an order of magnitude lighter and more fuel-efficient and will have a similar savings in logistics tail compared with a system that has the same capability but is based some 2,000 miles from the action. Recent global political events make it clear that any reliance on foreign basing may be problematic in some future conflicts. A fleet-based UAV network would allow line-of-sight relay to the battlespace without the large antennas and severe UAV power drains of satellite communications. Critical information could be fed from the fleet into the national grid via satellite. Since the Navy is presumably the first Service to project force into a region, the UAV communications grid would arrive with it and thus be available for all of the Services to use. Once the Marine Corps has established a secure base in theater, part or all of the maintenance of this UAV grid can be moved on land if that is logistically superior to continued fleet basing.

One particular advantage of the fleet-based UAV grid is that the speed-of-light delay is negligible. It is axiomatic in autonomous vehicle development (at least for those hoping to field systems of acceptable complexity and cost) that one should close only the control loops on the vehicle that are essential owing to latency or bandwidth concerns. In this case, the fundamental bandwidth and latency limitations are so minor that there is actually no formal need to close any of the loops on the vehicle. But in fact it is so trivial to make the vehicle perform behaviors such as to navigate through a series of GPS waypoints that it would be pointless not to include this feature, at the very least so that the vehicle can both finish its primary mission and return back to base if communications are lost.

Indeed, because a GIG/UAV communications system should provide abundant bandwidth even when there are huge numbers of UAVs in the theater, the one reason for onboard intelligence is health monitoring and fault recovery, especially as related to the communications system. Fortunately there has been considerable progress in such autonomous health monitoring and fault recovery. Other autonomy functions can augment or replace human operator intelligence at the control station first (where computing mass and power are effectively infinite). Later, these functions may migrate up to the vehicle in an orderly fashion as Moore's law reduces the mass, power, and cost of ever-more-sophisticated onboard computers. Using current-generation commercial off-the-shelf processing at the control station, the state of autonomy development is such that it should be possible to have a single human operator control multiple vehicles within the very near future. Presumably humans will be involved in target identification and weapons release authority for a very long time. Also, the ability of an intelligent adversary to "spoof" even (maybe especially) sophisticated automated systems should not be underestimated. The need for human "eyes on target" (via remote sensing) to satisfy any plausible rules of engagement is a powerful reason to design a system that has adequate bandwidth to transmit the necessary high-resolution images without much delay. This architecture effectively makes autonomy enhancing but not enabling, which is reassuring considering the slow pace of autonomy successes over the past few decades.

The GIG communications architecture permits telepresence for the human operator so long as the operator is in theater. If the geosynchronous relay satellite component of the GIG is used (e.g., for operators in the CONUS), then the speed-of-light latency will be too great for fleet launch and retrieval operations. Thus, at a minimum, pilots who manage the launch and recovery of the UAVs should be based in the fleet. It may be desirable to hand off control to other pilots located elsewhere during the mission. Technology for launch and recovery of UUVs from the torpedo tubes of submarines is already in an advanced state of development. UUVs with perhaps weeks of endurance that cannot fit in a standard torpedo tube, such as might be needed for a submarine track-and-trail mission, will need new developments for launch and recovery.

The situation for communications with underwater vehicles is completely different from that for UAVs. Those UUVs whose mission allows them to continuously or periodically rise to the surface (to snorkel for air-breathing power, get a GPS fix, and so on) can use tight high-frequency beams to the UAV network and the GIG system for high-bandwidth communications. Fortunately, many or most UUV missions fall into this category.

One of the most demanding missions is searching for mines emplaced on or under the seafloor. This effort requires that the vehicle descend to 100 m or more of depth so that short-range sensors can locate the mines. However, it is a relatively modest mission demand to require that the vehicle bring a low-observable antenna to the surface every few kilometers, getting a GPS fix and allowing the exchange of huge amounts of data with the GIG/UAV network. Thus, the principal onboard autonomy requirement for the UUV is to be able to navigate effectively for a period of an hour or so, through a combination of inertial and topography-matching techniques, both of which are relatively mature. (Also, in some situations acoustic beacons can be emplaced to form a local underwater "GPS-like" navigation grid.) Since navigation can be fairly accurate, it is acceptable to have a strategy by which, for example, minelike objects are cataloged along with their detailed sensor profiles, which are then reviewed by human and sophisticated offboard processing following a GIG interchange, with the UUV being sent back to those objects that are determined to be worthy of further scrutiny, tagging, or destruction. There are other attractive architectures for UUVs, such as using acoustic communications to surface transponders into the GIG network, although acoustic communications create a distinctive broadcast signature that tightly focused beams useable by UAVs will not have. This signature might compromise certain missions.

IN SUMMARY

It can be concluded that a very attractive system of autonomous vehicles is composed of a collection of relatively slow undersea and airborne vehicles, each with a launch mass of 1 ton or a few tons and the usual streamlined form factor. These vehicles are essentially flying fuel tanks that can be capable of relatively long endurance, so a large effort does not have to be spent in nearly continuous launch-and-recovery operations.

Each vehicle can return huge amounts of data (at gigabits per second, if necessary) for ship- or ground-based processing. Generally it is not important to miniaturize sensors so that what would be a standard sensor fits in a miniature vehicle, since the basic physics favors sensor apertures more appropriate for the moderate-sized vehicle. To avoid very long delays in getting on-station, these "slow" UAVs should be based close to the action (e.g., on the fleet). Recent political events show that reliance on foreign powers for land basing or overflight rights is fragile, arguing in favor of ship basing.

Needed onboard autonomy can be modest, at least at first, since there are no serious latency or bandwidth limits imposed by the physics of the deployment. The ability to navigate through GPS waypoints is trivial to include. Automated health monitoring, fault recovery, and return-to-base should be relatively easy to implement, especially if effort is focused initially on situations involving loss of communications. At first, all serious data processing can be done at the base station. As the technology advances to do this processing automatically, it will progressively reduce the number of human operators per vehicle and the overall system life-cycle cost. At the very least, humans will certainly be required for a very long time for weapons-release authority and for target identification to outwit the camouflage, concealment, and deception of an intelligent adversary.

Each UAV would have multiple, gimbaled, pointing platforms that are able to maintain accurate pointing and tracking. Some would be gimbaled mirrors used for sensing, and some would be the gimbaled dishes used for high-bandwidth communications, employing focused beams at high frequencies. In all cases they can and perhaps should be inertially stabilized so that they only slew in inertial space precisely as commanded but do not require constant, high-rate servoing in order to reject airframe disturbances. This need suggests that all can use the same pointing technology and common hardware as much as possible to reduce costs, and that it may be desirable to incorporate a reaction wheel in each reflector assembly (e.g., spin the reflecting dish as is done on the Sidewinder missile) to provide inertial stabilization of each reflector. Since it is desired that each UAV support multiple communications channels and relays, it may be that one or more pods on each wing should provide such gimbaled pointing platforms in both the forward and aft directions, with as large an unobstructed field of view and range of gimbal motion as possible. It is important not to underestimate the value of UAVs as high-bandwidth communications relays, a role that may ultimately approach or eclipse their importance as information-gathering devices.

This scaling discussion does not apply to ground vehicles, but the complexity of negotiating jungles, urban rubble piles, areas inside buildings and sewers, and so on with a ground vehicle is so daunting that it leads one to examine the ducted-fan, vertical-takeoff-and-landing, organic air vehicles and micro-air-vehicles now being developed under funding from the Defense Advanced Research Projects Agency. This scaling analysis does apply to them, and since they are small, they have low range and endurance. As such, they are presumably close to the ground troops that deploy them and so can be recovered, refueled, and redeployed as needed, to stay ahead of the forward troops. Also, they can "perch and stare" for longer endurance. Larger, tanklike autonomous ground vehicles that will be used by the Marine Corps will presumably be developed by the Army (i.e., as part of the Future Combat System, which relies heavily on robotic vehicles as part of its basic architecture). Such vehicles are outside the scope of this appendix, except that they can benefit greatly from the UAV communications network.

It is important to recognize that "humanlike performance" will perhaps be achieved with fully autonomous machines, but probably not for many decades. That is because the human brain represents some 10^{17} operations per second of equivalent computing performance ($\sim 10^{11}$ neurons, each with a few thousand synapses operating at a few hundred hertz). Today's desktop processors perform about 10^9 operations per second. Assuming that Moore's law continues unabated—increasing processor throughput by a factor of two every 18 months as progression is made from planar two-dimensional structures to fully integrated three-dimensional computing structures—it will take 40 years to close the gap. Very clever software may reduce the computing requirement by a few orders of magnitude, but it still seems quite possible that humanlike performance in compact, affordable systems is 30 to 50 years away. (The largest supercomputers may reach rough "human equivalence" within a decade.) A key point for the deployment of UAVs in support of naval operations is that the basic physics does not impose a serious bandwidth or latency constraint (unlike, for example, the case of planetary exploration by the National Aeronautics and Space Administration) that prevents appropriate levels of human involvement with the unmanned vehicles; this feature will allow the total system to have performance comparable to that of a manned system with much less cost and risk. The GIG communications architecture being deployed by the Office of the Secretary of Defense appears to offer all of the necessary features for high-speed, point-to-point communications using secure, focused beams at high frequency. Autonomy (in the sense of onboard computing of those functions that are usually thought to require human intelligence) can be infused as it becomes available, to further reduce cost or risk or to increase performance. But advanced autonomy is not "enabling" except for those missions (some urban, cave, or tunnel warfare scenarios) in which line-of-sight communications cannot be made available.

C

Unmanned Aerial Vehicles: System Descriptions

The unmanned aerial vehicle (UAV) systems directly relevant to the section "Conclusions and Recommendations" in Chapter 4, "Unmanned Aerial Vehicles: Capabilities and Potential," of this report fall into two operational categories: (1) intelligence, surveillance, and reconnaissance (ISR) and (2) strike (i.e., uninhabited combat air vehicle (UCAV)). Other UAVs not related to the findings and recommendations but still of current or potential interest for naval operations are described at the end of this appendix, in the section entitled "Other Unmanned Aerial Vehicles of Interest." Readers interested in broader and/or more detailed information are referred to the Department of Defense (DOD) report *Unmanned Aerial Vehicles Roadmap 2002-2027*.[1] As noted, system descriptions of the UAVs in this appendix are reproduced from that report.

LONG-ENDURANCE, INTELLIGENCE, SURVEILLANCE, AND RECONNAISSANCE UNMANNED AERIAL VEHICLES

To date, the DOD's long-endurance UAVs have been operationally employed exclusively by the Air Force in the form of the piston-engine Predator A (designated RQ-1) and the turbofan-powered Global Hawk (RQ-4), both of which had their genesis as Defense Advanced Research Projects Agency (DARPA) programs. The Air Force will also soon deploy the turboprop-powered and higher-

[1]Office of the Secretary of Defense. 2002. *Unmanned Aerial Vehicles Roadmap 2002-2027,* Department of Defense, Washington, D.C., December. Available online at http://www.acq.osd.mil/usd/uav_roadmap.pdf. Accessed June 2005.

speed, larger-payload Predator B (RQ-9). As is well known, both the Predator and the Global Hawk proved extremely valuable for conducting intelligent preparation of the battlefield and maintaining operational situation awareness during recent conflicts. Predator A has also been armed with Hellfire missiles (MQ-1) and fills a unique, ISR plus long-endurance strike platform role. An interesting historical note is that the Navy served as the procurement agency for early Predator acquisitions and still has two early systems in inventory. Nonetheless, the dominant Service in the long-endurance UAV operations has been the Air Force, and the issue for naval operations in the vehicle class is straightforward—should the Navy rely on the Air Force to provide land-based, long-endurance ISR support or are organic naval assets required? The Marine Corps does rely on the Air Force for this support. The programs described below are directly related to this issue (see the section "Conclusions and Recommendations" in Chapter 4) and are excerpted directly from the DOD report *Unmanned Aerial Vehicles Roadmap 2002-2027.*

RQ-4 Global Hawk

The Air Force RQ-4 Global Hawk is a high altitude, long endurance UAV designed to provide wide area coverage of up to 40,000 nm^2 per day. It successfully completed its Military Utility Assessment, the final phase of its ACTD, in June 2000, and transitioned into Engineering and Manufacturing Development (EMD) in March 2001. It takes off and lands conventionally on a runway and currently carries a 1950 lb payload for up to 32 hours. Global Hawk carries both an EO/IR sensor and a SAR with moving target indicator (MTI) capability, allowing day/night, all-weather reconnaissance. Sensor data is relayed over Common Data Link (CDL) line-of-sight (LOS) (X-band) and/or beyond-line-of-sight (BLOS) (Ku-band SATCOM) data links to its Mission Control Element (MCE), which distributes imagery to up to seven theater exploitation systems. Residuals from the ACTD consisted of four aircraft and two ground control stations. Two more ACTD advanced aircraft will be delivered in early FY03 to support EMD and contingency operations. The Air Force has budgeted for 27 production aircraft in FY02-07, and plans a total fleet of 51. The Air Force plans to add other sensor capabilities in a spiral development process as this fleet is procured. Ground stations in theaters equipped with the Common Imagery Processor (CIP) will eventually be able to receive Global Hawk imagery directly. IOC for Imagery Intelligence (IMINT)-equipped aircraft is expected to occur in FY06. [p. 8]

MQ-1 Predator

The Air Force MQ-1 Predator was one of the initial ACTDs in 1994 and transitioned to an Air Force program in 1997. It takes off and lands conventionally on

MQ-9 Predator B/General Atomics/Air Force

Weight:	10,000 lb
Length:	36.2 ft
Wingspan:	64 ft
Payload:	750 lb internal/3000 lb external
Ceiling:	45,000 ft
Radius:	400 nm
Endurance:	24+ hr

FIGURE C.1 MQ-9 Predator B. SOURCE: Office of the Secretary of Defense. 2002. *Unmanned Aerial Vehicles Roadmap 2002-2027,* Department of Defense, Washington, D.C., December, p. 10.

a runway and can carry a maximum 450 lb payload for 24+ hours. Operationally, it is flown with a gimbaled electro-optical/infrared (EO/IR) sensor and a SAR, giving it a day/night, all-weather (within aircraft limits) reconnaissance capability. It uses either a line-of-sight (C-band) or a beyond-line-of-sight (Ku-band Satellite Communications (SATCOM)) data link to relay color video in real time to commanders. Since 1995, Predator has flown surveillance missions over Iraq, Bosnia, Kosovo, and Afghanistan. In 2001, the Air Force demonstrated the ability to employ Hellfire missiles from the Predator, leading to its designation being changed from RQ-1 to MQ-1 to reflect its multi-mission capability. The Air Force operates 12 systems in three Predator squadrons and is building toward a force of 25 systems consisting of a mix of 100 MQ-1 and MQ-9 aircraft. [p. 6]

MQ-9 Predator B

Predator B [see Figure C.1] is a larger, more capable, turboprop-engined version of the Air Force MQ-1B/Predator developed jointly by NASA and General Atomics as a high altitude endurance UAV for science payloads. Its initial flight occurred in February 2001. The Office of the Secretary of Defense acquired both existing Predator B prototypes in October 2001 for evaluation by the Air Force. With the capability to carry up to ten Hellfire missiles, the MQ-9 could serve as the killer portion of a MQ-1/MQ-9 hunter/killer UAV team. Current funding plans are to acquire nine MQ-9s, although Congress has expressed interest in increasing the procurement. [pp. 9-10]

RELATIONSHIP TO BROAD AREA MARITIME SURVEILLANCE

In the "Conclusions and Recommendations" section of Chapter 4, it is observed that Broad Area Maritime Surveillance (BAMS) requirements might be met in a more cost-effective fashion if the Navy and the Air Force put together an initiative based on joint operation of RQ-4 Global Hawk and/or RQ-1/RQ-1B Predator or MQ-9 Predator B systems. The following is a short synopsis of the BAMS program objective as described in the DOD *Unmanned Aerial Vehicles Roadmap 2002-2027*.

> In December 2001, Secretary of the Navy directed, on an accelerated basis, the acquisition of an unmanned persistent intelligence, surveillance, and reconnaissance (ISR) capability in support of the warfighter. In response, the Navy developed a two-phased approach to rapidly acquire a Broad Area Maritime Surveillance (BAMS) UAV system using current available platforms to speed acquisition, sensor development, concept of operations (CONOPS) development and achieve low risk. The first phase, the Global Hawk Maritime Demonstration (GHMD), will procure two off-the-shelf Air Force Global Hawk UAV platforms with sensors modified for maritime ISR missions and associated ground equipment for Navy use in CONOPS development, technology validation and to conduct experimentation in a maritime environment. The second phase, the BAMS UAV Program, is a formal DoD acquisition initiated to develop, test, field and support a maritime patrol, reconnaissance, and strike support UAV system. An Analysis of Alternatives is currently underway that will be used to help determine the platform and force structure required to support the BAMS UAV mission. An estimated 50 air vehicles are planned but the final number will be adjusted when the objective platform is selected. The BAMS UAV Initial Operating Capability (IOC) is currently planned for FY09. [pp. 8-9]

TACTICAL INTELLIGENCE, SURVEILLANCE, AND RECONNAISSANCE

Tactical UAVs include both conventional-takeoff-and-landing tactical unmanned aerial vehicle (TUAV) and vertical-takeoff-and-landing tactical unmanned aerial vehicle (VTUAV) types. In this UAV arena, the Navy and Marine Corps (together with the Army) served as vanguard Services when they operationally employed the Israeli-developed Pioneer TUAV in 1986. Navy applications were as spotters for naval fires. Unfortunately, the challenges of operating a fixed-wing aircraft from surface ships were daunting (e.g., recovery in a net) and the Pioneers were withdrawn from service with the fleet. Although Pioneer continues to serve with the Marine Corps, its ship-based shortfall spawned a requirement for a vertical-takeoff-and-landing system and eventual selection of Fire Scout to meet the Navy UAV requirements. Fire Scout continues in development and has performed well in land-based flight trials. The Marine Corps has a need for a sea-based VTUAV that will support the Ship-to-Objective Maneuver (STOM) concept at ranges out to 200 nautical miles. A related development is the Bell "Eagle Eye," a tilt-rotor-based UAV. It was "down-selected" in favor of the

RQ-2 Pioneer/Pioneer UAVs, Inc./USMC

Weight:	452 lb
Length:	14 ft
Wingspan:	17 ft
Payload:	75 lb
Ceiling:	15,000 ft
Radius:	100 nm
Endurance:	5 hr

FIGURE C.2 RQ-2 Pioneer. SOURCE: Office of the Secretary of Defense. 2002. *Unmanned Aerial Vehicles Roadmap 2002-2027,* Department of Defense, Washington, D.C., December, p. 7.

Fire Scout but subsequently selected by the Coast Guard to meet its ship-based UAV requirements under the Deep Water program. Much of the information on these programs in the following sections is excerpted from the DOD *Unmanned Aerial Vehicles Roadmap 2002-2027.*

RQ-2 Pioneer

The joint Navy/Marine Corps/Army TUAV was based on an Israeli design and served as the vanguard UAV for naval operations. Although scheduled for being phased out of operational service, it is significant for its operational lessons learned, which greatly influence current attitudes toward UAVs in this capability class. Following is a short synopsis of the program.

> The Navy/Marine RQ-2 Pioneer [see Figure C.2] has served with Navy, Marine, and Army units, deploying aboard ship and ashore since 1986. Initially deployed aboard battleships to provide gunnery spotting, its mission evolved into reconnaissance and surveillance, primarily for amphibious forces. Launched by rocket assist (shipboard), by catapult, or from a runway, it recovers into a net (shipboard) or with arresting gear after flying up to 5 hours with a 75 lb payload. It currently flies with a gimbaled EO/IR sensor, relaying analog video in real time via a C-band line-of-sight (LOS) data link. Since 1991, Pioneer has flown reconnaissance missions during the Persian Gulf, Bosnia, and Kosovo conflicts. The Navy ceased Pioneer operations at the end of FY02 and transferred their assets to the Marine Corps. The Marine Corps is embarking on improvements to the Pioneer to extend their operations with it until FY09 or a replacement is fielded. [p. 6]

RQ-7 Shadow 200

The Army selected the RQ-7 Shadow 200 (formerly Tactical UAV (TUAV)) in December 1999 to meet its Brigade level UAV requirement for support to ground maneuver commanders. Catapulted from a rail, it is recovered with the aid of arresting gear. It will be capable of remaining on station for 4 hours at 50 km (27 nm) with a payload of 60 lb. Its gimbaled EO/IR sensor will relay video in real time via a C-band LOS data link. Current funding allows the Army to procure 39 systems of four aircraft each for the active duty forces and 2 systems of four aircraft each for the reserve forces. Approval for full rate production (acquisition Milestone C) and IOC occurred in September 2002. The Army's acquisition objective, with the inclusion of the Army Reserve component, is 83 total systems. [p. 7]

RQ-8 Fire Scout

The Fire Scout vertical take-off and landing (VTOL) tactical UAV (VTUAV) program is currently in EMD and LRIP. Five Air Vehicles and four Ground Control Stations are now in Developmental Testing. A significant number of successful test flights have been accomplished demonstrating autonomous flight, Tactical Control Data Link (TCDL) operations, Multi-Mission Payload performance and Ground Control Station operations. Fire Scout Tactical Control System developmental testing is scheduled for mid-FY03. With continuing FY03 EMD testing successes, the Navy has recognized the VTUAV program value for the emerging Landing Craft Support series of surface vessels. The Navy is currently reviewing the VTUAV Operational Requirements Document (ORD) and funding has been added to the FY04 budget to continue development and to conduct shipboard demonstrations. Additional out year funding for VTUAV is being considered for future development and production. [p. 9]

Eagle Eye

The air vehicle in Figure C.3 is based on MV-22 tilt-rotor technology and offers a speed and endurance advantage over conventional rotary wing vehicles. The advantage derives from the inherent benefits of the tilt-rotor concept, since during forward flight the rotors are repositioned ninety degrees and act as large propellers with most lift provided by the wing similar to a conventional aircraft.

HUMAN-PORTABLE OR SMALL-UNIT UNMANNED AERIAL VEHICLES

Naval forces have been the vanguard Services for the development and introduction of small UAVs that operate in direct support of small-unit operations. To

Eagle Eye Tilt Rotor
Weight: 2250 lb
Length: 17.9 ft
Rotorspan: 15.2 ft
Payload: 100-500 lb
Ceiling: 20,000 ft
Radius: 160 nmi
Endurance: 8 hrs

FIGURE C.3 Eagle Eye Tilt Rotor. SOURCE: Courtesy of U.S. Air Force

FQM-151 Pointer/AeroVironment/Navy

Weight:	10 lb
Length:	6 ft
Wingspan:	9 ft
Payload:	2 lb
Ceiling:	1000 ft
Radius:	3 nm
Endurance:	1 hr

FIGURE C.4 FQM-151 Pointer. SOURCE: Office of the Secretary of Defense. 2002. *Unmanned Aerial Vehicles Roadmap 2002-2027,* Department of Defense, Washington, D.C., December, p. 15.

date, two such systems have been fielded, the Pointer and the Dragon Eye, both of which are battery-powered. The descriptions in the following subsections are excerpted from the DOD *Unmanned Aerial Vehicles Roadmap 2002-2027*.

FQM-151 Pointer

Approximately 100 hand-launched, battery powered FQM-151/Pointers [see Figure C.4] have been acquired by the Marines and the Army since 1989 and were employed in the Gulf War. Most recently, the Navy used Pointer to help clear the Vieques, Puerto Rico, range of demonstrators, and the Army acquired six systems for use at its Military Operations in Urban Terrain (MOUT) facility at Ft Benning, GA. Pointers have served as testbeds for numerous miniaturized

Dragon Eye/BAI Aerosystems; AeroVironment/Marine Corps

Weight:	4.5 lb
Length:	2.4 ft
Wingspan:	3.8 ft
Payload:	1 lb
Ceiling:	1000 ft
Radius:	2.5 nm
Endurance:	45-60 min

FIGURE C.5 Dragon Eye. SOURCE: Office of the Secretary of Defense. 2002. *Unmanned Aerial Vehicles Roadmap 2002-2027,* Department of Defense, Washington, D.C., December, p. 10.

sensors (e.g., uncooled IR cameras and chemical agent detectors) and have performed demonstrations with the Drug Enforcement Agency, National Guard, and special operations forces. [p. 15]

Dragon Eye

Dragon Eye [see Figure C.5] is a mini-UAV (4-foot wingspan and 4 lb weight) developed as the Marine Corps Warfighting Laboratory's (MCWL) answer to the Navy's Over-The-Hill Reconnaissance Initiative and the Marines' Interim Small Unit Remote Scouting System (I-SURSS) requirement. The potential Navy version is referred to as *Sea ALL. Dragon Eye* fulfills the first tier of the Marine Corps UAV roadmap by providing the company/platoon/squad level with an organic RSTA capability out to 10 km (5 nm). It can carry either an EO, IR, or low light TV as its sensor. The first prototype flew in May 2000, with low rate production contracts (40 aircraft) awarded to AeroVironment and BAI Aerosystems in July 2001. By March 2003 the Marine Corps will award a production contract to one of these two vendors following user operational assessment. IOC is planned for the Fall of 2003. A total of 311 systems, each with 3 aircraft and one ground station, are planned. [p. 10]

STRIKE UNMANNED AERIAL VEHICLES OR UNINHABITED COMBAT AIR VEHICLES

The current Navy/Air Force/DARPA UCAV program envisions the development of a single overall system capable of meeting requirements for both Services. The original Air Force vision was a land-based system intended primarily for the suppression of enemy air defense (SEAD) mission with strike and ISR as fallout capabilities. The Navy vision was for a carrier-based system for ISR, with SEAD and strike as fallout capabilities of manned strike missions. Currently there are two competitors for the Joint Unmanned Combat Air System program. One is a derivative of the DARPA/Air Force/Boeing X-45 currently under development to meet Air Force SEAD requirements. The other is the Northrop Grumman X-47 Pegasus. Both concepts have flown in prototype form. From the naval perspective, the key technology challenge for both is carrier suitability and the ability to launch and recover unmanned vehicles from a very busy carrier. One enabler for this capability is the Joint Precision Approach and Landing System (JPALS) development, described in the section entitled "Autoland Systems," in Chapter 4. The following is a short synopsis of both the Boeing and Northrop Grumman concepts as described in the DOD *Unmanned Aerial Vehicles Roadmap 2002-2027*. Since that time, however, a joint UCAV program office has been formed under the leadership of DARPA, with the objective of developing a single UCAV system to meet both Navy and Air Force requirements, similar to the effort under way on the F-35 Joint Strike Fighter.

Navy Unmanned Combat Air Vehicle

> The DARPA/Office of Naval Research's Naval Unmanned Combat Air Vehicle (UCAV-N) Advanced Technology Demonstration (ATD) Program is examining the critical technologies and systems needed to operate a large autonomous UAV from a Navy aircraft carrier. The system is envisioned to be multi-mission capable with an initial focus on tactical surveillance, evolving into a SEAD/strike system as the concept matures. The UCAV-N acquisition cost goal is 50 percent of the Navy's F-35 variant, and its operating cost goal is 50 percent of the F/A-18C/D's. The Naval Unmanned Combat Air Vehicle (UCAV-N) ATD program will be merged with the current Air Force UCAV program under a Joint Program office. Both Northrop-Grumman (X-47A Pegasus) and Boeing (X-46) will partake in a Joint Strike Fighter (JSF)-like competition to meet Air Force and Navy requirements. First flight of a shore-based catapult and arrested-landing-capable UCAV-N demonstrator is expected in late FY06. Fourteen Air Force UCAV's are scheduled for delivery by FY08 while the Naval UCAV is planned to achieve IOC before 2015. [p. 12]

Air Force Unmanned Combat Air Vehicle

> The joint Defense Advanced Research Projects Agency (DARPA)/Air Force UCAV System Demonstration Program (SDP) [see Figure C.6] is designed to demonstrate the technological feasibility, military utility, and operational value of a UCAV system to effectively and affordably prosecute Suppression of Enemy Air Defenses (SEAD) and strike missions in the 2010+ high threat environment.

UCAV/Boeing/DARPA Air Force

	X-45A	X-45C
Weight:	12,000 lb	35,000 lb
Length:	26.3 ft	36 ft
Wingspan:	33.8 ft	48 ft
Payload:	1,500 lb	4,500 lb
Ceiling:	35,000 ft	40,000 ft
Speed:	0.75 M	0.85 M
Endurance/ Combat Radius:	1.5 hr	1,000 nm + 2 hr loiter

FIGURE C.6 UCAV-N. SOURCE: Office of the Secretary of Defense. 2002. *Unmanned Aerial Vehicles Roadmap 2002-2027,* Department of Defense, Washington, D.C., December, p. 12.

> Two X-45A (Spiral 0) demonstrator air vehicles have been delivered to NASA's Dryden facility at Edwards AFB; first flight occurred in May 2002. Design has started on the next generation X-45C (Spiral 1) air vehicle, which will add stealth characteristics; first flight is expected in late 2005. The Air Force has budgeted for up to 36 UCAV systems for delivery by 2010 for early operational capability and warfighter assessment. An effects-based spiral development approach is envisioned to rapidly field initial UCAV capability and expand that capability as technology and funding permit. [p. 11]

OTHER UNMANNED AERIAL VEHICLE PROGRAMS

Following is a series of short synopses of other UAV vehicles or programs that are addressed in the committee's conclusions and recommendations. The descriptions are excerpted from the DOD *Unmanned Aerial Vehicles Roadmap 2002-2027.*

Advanced Air Vehicle UAV Program of the Defense Advanced Research Projects Agency

> In addition to its involvement in three UCAV/UCAR demonstration programs, the Defense Advanced Research Projects Agency (DARPA) is currently sponsoring five other innovative UAV designs. The Advanced Air Vehicle (AAV) program is developing two unmanned rotorcraft projects, the Boeing X-50 Dragonfly Canard Rotor Wing (CRW) and the Frontier A160 Hummingbird. The attributes being explored under the AAV program are speed, altitude, and endurance. The goal is to substantially improve the performance of rotorcraft to

levels nearing that of fixed wing aircraft. The *Dragonfly* will demonstrate the ability to takeoff and land from a hover, then transition to fixed wing flight for cruise, using its stopped rotor as its wing. The result will be a high speed (400+ kts) rotorcraft. CRW is expected to fly in 2003. The other AAV project is the *Hummingbird*, which uses a hingeless, rigid rotor to achieve a high endurance (24+ hrs), high altitude (30,000 ft) rotorcraft. Its first flight occurred in January 2002. [p. 18]

Unmanned Combat Armed Rotorcraft

The Unmanned Combat Armed Rotorcraft (UCAR) is a DARPA/Army program begun in FY02 to develop an unmanned attack helicopter for the armed reconnaissance and attack missions at 20 to 40 percent the acquisition cost of a RAH-66 Comanche and 20-50 percent of the operating cost of an AH-64 Apache. This system will be a critical component of the Army Objective Force system-of-systems architecture. Phase I study contracts to conduct system trades and concept exploration were awarded to Boeing, Lockheed Martin, Northrop Grumman, and Sikorsky in May 2002. First flight is anticipated in 2006, leading to an acquisition decision in 2009. With *UCAR*, the Army, Navy, and Air Force each now have unmanned combat aircraft initiatives. [p. 13]

Micro Air Vehicles

DARPA and the Army are exploring designs for both Micro Air Vehicles (MAVs)—aircraft no more than 6 to 12 inches in any dimension—and a slightly larger Organic Air Vehicle (OAV) to accompany the Army's Future Combat System's (FCS) robotic ground vehicles. The primary difference between the two systems is the MAV is focused on a small system suitable for backpack deployment and single-man operation, whereas the OAV is aimed at a larger system transported aboard one of the FCS ground vehicles. Honeywell was awarded an agreement to develop and demonstrate the OAV concept, and Robotic Technology, Inc., was subcontracted to develop the OAV under the FCS contract. The OAV is envisioned as a scalable-in-size UAV that can be launched and controlled from a HMMWV or robotic vehicle to provide over-the-hill RSTA. It is to be demonstrated with other FCS components at CECOM in 2003. Allied Aerospace has been awarded an agreement as part of the MAV ACTD, which pushes the envelope in small, lightweight propulsion, sensing, and communication technologies. Following its Military Utility Assessment (MUA) in FY04, 25 MAV systems are to transfer to the Army in FY05. A third effort, by DARPA's Synthetic Multifunctional Materials program, has developed a 6-ounce MAV, the AeroVironment Wasp, having an integrated wing-and-battery which has flown for 1.8 hours. [pp. 18-19]

Finder/NRL/ACTD

Weight:	59 lb
Length:	5.25 ft
Wingspan:	8.6 ft
Payload:	13.5 lb
Ceiling:	15,000 ft
Radius:	50 nm
Endurance:	10 hr

FIGURE C.7 Finder. SOURCE: Office of the Secretary of Defense. 2002. *Unmanned Aerial Vehicles Roadmap 2002-2027,* Department of Defense, Washington, D.C., December, p. 16.

Counter Proliferation II ACTD

> The Counter Proliferation II ACTD [see Figure C.7], sponsored by the Defense Threat Reduction Agency (DTRA), envisions deploying two mini-UAVs (*Finders*) from a larger Predator UAV to conduct point detection of chemical agents. The employment concept for *Finder* (Flight Inserted Detection Expendable for Reconnaissance) is to fly up to 50 nm from Predator and loiter in the vicinity of a suspected chemical agent cloud for up to 2 hours, passing its sensor data back to the Predator for relay to warfighters and/or collecting air samples for recovery by ground forces for analysis. Eight Finder systems (16 vehicles) are to remain as residuals when the ACTD ends in 2004. [pp. 15-16]

OTHER UNMANNED AERIAL VEHICLES OF INTEREST

Theater-Level ISR (Under Consideration)

Sensorcraft is under consideration by the Air Force as a next-generation ISR platform technology demonstrator. This is one of the programs recommended to be monitored for its potential applications to future naval operations. The following is a short synopsis of the program as described in the DOD *Unmanned Aerial Vehicles Roadmap 2002-2027.*

> Sensorcraft [see Figure C.8] is an Air Force Research Laboratory (AFRL) concept for a sensor-driven UAV design; multiple definition contracts were awarded at the start of FY01. Its intent is to optimize a configuration for future airborne radar imaging and signals collection, then design the airframe, flight controls, and propulsion to conform to this configuration. The initiative inte-

FIGURE C.8 Sensorcraft/Air Force (artist concept). SOURCE: Office of the Secretary of Defense. 2002. *Unmanned Aerial Vehicles Roadmap 2002-2027,* Department of Defense, Washington, D.C., December, p. 17.

> grates UAV-related efforts across a number of AFRL directorates and technology areas. [p. 17]

Unit/Individual-Level ISR (Developmental)

A number of organizations have continued the development of small and mini-size UAVs to meet the ISR needs of individual ground units. The committee's conclusions and recommendations in Chapter 4 suggest that the Marine Corps continue to pursue and/or monitor UAV programs in this size class. The following are short synopses of some mini-UAV programs described in the DOD *Unmanned Aerial Vehicles Roadmap 2002-2027* that the committee believes should be proactively monitored.

> *FPASS* [see Figure C.9] is designed for ease of use by Air Force security personnel to improve situational awareness of the force protection battlespace by conducting area surveillance, patrolling base perimeters and runway approach/departure paths, and performing convoy over watch. The Air Force Electronic Systems Center developed *FPASS* to address a 1999 U.S. Central Command (CENTCOM) request for enhancing security at overseas bases. CENTAF refers to the *FPASS* vehicle as *Desert Hawk*. Battery-powered, it is launched with the aid of a bungee cord and equipped with either a visible or an uncooled IR video sensor. Each system consists of six aircraft and a laptop control station. Delivery of initial systems began in July 2002. [pp. 10-11]

> Neptune [see Figure C.10] is a new tactical UAV design optimized for at-sea launch and recovery. Carried in a 72 × 30 × 20 inch case that transforms into a

FPASS/Lockheed Martin/Air Force

Weight:	5 lb
Length:	3 ft
Wingspan:	4 ft
Payload:	1 lb
Ceiling:	1,000 ft
Radius:	5 nm
Endurance:	60-90 min

FIGURE C.9 FPASS. SOURCE: Office of the Secretary of Defense. 2002. *Unmanned Aerial Vehicles Roadmap 2002-2027,* Department of Defense, Washington, D.C., December, p. 11.

> pneumatic launcher, it can be launched from small vessels and recovered in open water. It can carry IR or color video sensors, or can be used to drop small payloads. Its digital data link is designed to minimize multipath effects over water. First flight occurred in January 2002, and an initial production contract was awarded to DRS Unmanned Technologies in March 2002. [p. 11]

Combat Support

Currently there are no UAV programs focused primarily on combat support missions. Many of the programs already described, however, have combat support capabilities. For example, Global Hawk and A-160 have inherent capability to function as a theater-level communications relay. The UAV program for SEAD and strike is the J-UCAS program.

Neptune/DRS Unmanned Technologies/Navy

Weight:	80 lb
Length:	6 ft
Wingspan:	7 ft
Payload:	20 lb
Ceiling:	8,000 ft
Radius:	40 nm
Endurance:	4 hr

FIGURE C.10 Neptune. SOURCE: Office of the Secretary of Defense. 2002. *Unmanned Aerial Vehicles Roadmap 2002-2027,* Department of Defense, Washington, D.C., December, p. 11.

Other Unmanned Aerial Vehicle Developments

There have been a number of UAV developments undertaken outside the DOD that have either application and/or significance for naval operations. For example, NASA development of the solar-powered helicopters could have future application as an extreme-endurance ISR platform. Even though these systems are relatively fragile technology demonstrators, with further development, operationally useful concepts might be possible. The NASA Altair (similar to Predator B) might also have application. Similarly, the privately developed Insitu Aerosonde global range mini-UAV and the commercially available Yamaha Rmax helicopter could also have naval applications.

D

Acronyms and Abbreviations

AAV	advanced air vehicle
ACLS	Automated Carrier Landing System
ACOMMS	acoustic communications systems
ACTD	Advanced Concept Technology Demonstration
AEHF	advanced extremely high frequency
AEW	airborne early warning
AFOSR	Air Force Office of Scientific Research
AFRL	Air Force Research Laboratory
AGS	Advanced Gun System
AGV	automated guided vehicle
AINS	Autonomous Intelligent Network and Systems (initiative)
AIP	Antisurface Warfare Improvement Program
ANS	Autonomous Navigation System
AOE	automated ordnance excavator
AOSN	Autonomous Ocean Sampling Network
ARL	Army Research Laboratory
ARPA	Advanced Research Projects Agency
ARTS	All Purpose Remote Transport System
ARV	armed robotic vehicle
ASH	autonomous search and hydrographic (vehicle)
ASM	antiship missile
ASN(RD&A)	Assistant Secretary of the Navy for Research, Development, and Acquisition
ASW	antisubmarine warfare

ATD	Advanced Technology Demonstration
AV	autonomous vehicle
AWACS	Airborne Warning and Control System
BAMS	Broad Area Maritime Surveillance
BPAUV	battlespace planning autonomous underwater vehicle
BUGS	Basic Unexploded Ordnance Gathering System
C2	command and control
C2S	Command and Control System
C2V	command and control vehicle
C3	command, control, and communications
C3I	command, control, communications, and intelligence
C3ISR	command, control, communications, intelligence, surveillance, and reconnaissance
C4	command, control, communications, and computers
C4I	command, control, communications, computers, and intelligence
C4ISR	command, control, communications, computers, intelligence, surveillance, and reconnaissance
CAP	combat air patrol
CAS	close air support
CDL	common data link
CECOM	Communications Electronics Command
CENTAF	U.S. Air Force, U.S. Central Command
CHBDL	common high-bandwidth data link
CLF	Combat Logistics Force
CMC	Commandant, Marine Corps
CNO	Chief of Naval Operations
CNR	Chief of Naval Research
COMINT	communications intelligence
CONOPS	concept(s) of operations
CONUS	continental United States
COTS	commercial off-the-shelf
CRW	canard rotor wing
CSG	Carrier Strike Group
CSP	constraint satisfaction problem
CTFF	Cell Transfer Frame Format
CU	Cruise Missiles and Unmanned Aerial Vehicles
CV/LH	aircraft carrier/amphibious assault ship
CWSP	Commercial Wideband Satellite Program
D7G	combat engineering vehicle

DARPA	Defense Advanced Research Projects Agency
DDG	destroyer
DD(X)	future destroyer
DEAD	destruction of enemy air defense
DEUCE	deployable universal combat earthmover
DOD	Department of Defense
DSV	deep submergence vehicle
ECM	electronic countermeasures
EHF	extremely high frequency
ELINT	electronic intelligence
EM/EO	electromagnetic/electro-optical
EMS	electromagnetic sensing
EMW	Expeditionary Maneuver Warfare
EOD	Explosive Ordnance Disposal
EO/IR	electro-optical/infrared
ESG	Expeditionary Strike Group
FCS	Future Combat System (Army)
FDI	fault detection and isolation
FDOA	frequency difference of arrival
FLT CNTL	flight control
FMEA	failure modes and effects analysis
FNC	Future Naval Capability
FOC	final operational capability
FP	force protection
FYDP	Future Years Defense Program
Gbps	gigabits per second
GBS	Global Broadcast System
GEOS	Geosynchronous Earth Orbit Satellite
GHMD	Global Hawk Maritime Demonstration
GHz	gigahertz
GIG	Global Information Grid
GIG-BE	Global Information Grid-Bandwidth Expansion
GIG-E	Globat Information Grid-Expansion
GMTI	ground moving target indicator
GPS	Global Positioning System
HAE	high-altitude and -endurance
HALE	high-altitude, long-endurance
HDTV	high-definition television
HMMWV	high mobility multipurpose wheeled vehicle

IMINT	imagery intelligence
IMU	inertial measurement unit
INMARSAT	International Maritime Satellite
INTELSAT	Intelligence Satellite
IOC	initial operating capability
IP	Internet Protocol
IR	infrared
ISR	intelligence, surveillance, and reconnaissance
ISR&T	intelligence, surveillance, reconnaissance, and targeting
JDAM	joint direct attack munition
JFACC	Joint Forces Air Component Commander
JMPS	Joint Mission Planning System
JPALS	Joint Precision Approach and Landing System
JPO	Joint Program Office
JSTARS	Joint Surveillance Target Attack Radar System
JTF	joint task force
JTRS	Joint Tactical Radio System
J-UCAS	Joint Unmanned Combat Air System
JWICS	Joint Worldwide Intelligence Communications System
kbps	kilobits per second
LADAR	laser detection and ranging
LCS	Littoral Combat Ship
L/D	lift to drag (ratio)
LD MRUUV	large-diameter multi-reconfigurable UUV
LDR	low data rate
LDUUV	long-distance unmanned undersea vehicle
LEOS	Low Earth Orbiting Satellite
LHA	amphibious assault ship (general purpose)
LHD	amphibious assault ship (multipurpose)
LIDAR	light detection and ranging
LMRS	Long-range Mine Reconnaissance System
LOA	level of autonomy
LOS	line of sight
LPD	amphibious transport dock
LRE	launch-and-recovery element
LRIP	low-rate initial production
MAE	medium-altitude and -endurance
MAGTF	Marine Air Ground Task Force
MARS	Mobile Autonomous Robot Software

Matilda	Mesa Associates' Tactical Integrated Light-force Deployment Assembly
MCCDC	Marine Corps Combat Development Command
MCE	mission control element
MCG&I	mapping, charting, geodesy,and imagery
MCWL	Marine Corps Warfighting Laboratory
MDA	Missile Defense Agency
MDARS-E/I	Mobile Detection Assessment Response System-Exterior/ Interior
MDR	medium data rate
MEB	Marine Expeditionary Brigade
MEF	Marine Expeditionary Force
MICA	Mixed Initiative Control of Automa-teams (program)
MILSATCOM	military satellite communications
MMS	Mission Management System
MPF	Maritime Prepositioning Force
MPF(F)	Maritime Prepositioning Force (Future)
MPM	mission payload module
MP-RTIP	Multi-Platform Radar Technology Insertion Program
MRD	Maritime Reconnaissance Demonstration (program)
MRUUV	multi-reconfigurable UUV
MTI	moving target indicator
MULE	multifunction utility logistics equipment (vehicle)
NASA	National Aeronautics and Space Administration
NAVAIR	Naval Air Systems Command
NAVSEA	Naval Sea Systems Command
NBC	nuclear, biological, and chemical
NII	Networks and Information Integration
NMRS	Near-term Mine Reconnaissance System
NRAC	Naval Research Advisory Committee
NRC	National Research Council
NRL	Naval Research Laboratory
NRO	National Reconnaissance Office
NSWC/CD	Naval Surface Warfare Center/Carderock Division
NUWC	Naval Undersea Warfare Center
NWDC	Navy Warfare Development Command
O&S	operations and support
OASD	Office of the Assistant Secretary of Defense
OAV	organic aerial vehicle
OCU	operator control unit
ODIS	Omni-Directional Inspection System

OMFTS	Operational Maneuver From the Sea
ONR	Office of Naval Research
OODA	observe-orient-decide-act
OPNAV	Office of the Chief of Naval Operations
OSD	Office of the Secretary of Defense
OSD(NII)	Office of the Secretary of Defense (Networks and Information Integration)
OTH	over-the-horizon
Packbot	versatile platform for military products
PEO	Program Executive Office
Perceptor	Perception for Offroad Robotics
PFPS	Portable Flight Planning System
PM-PSE	Program Manager-Physical Security Equipment
PMS	Program Management Office
PUMA	Precision Underwater Mapping System
QDR	Quadrennial Defense Review
R&D	research and development
RCSS	Remote Combat Support System
REMUS	Remote Environmental Monitoring Unit System
RF	radio frequency
RHIB	rigid hull inflatable boat
RMP	Radar Modernization Program
RMS	Remote Minehunting System
RONS	Remote Ordnance Neutralization System
ROV	remotely operated vehicle
RSTA	reconnaissance, surveillance, and target acquisition
RTIP	Radar Technology Improvement Program
S&T	science and technology
SA	situation awareness
SAHRV	semiautonomous hydrographic reconnaissance vehicle
SAM	surface-to-air missile
SAR	synthetic aperture radar
SAS	synthetic aperture sonar
SATCOM	satellite communications
SBR	space-based radar
SDD	System Development and Demonstration
SDR	Software for Distributed Robotics
SEAD	suppression of enemy air defense
SEAL	sea, air, and land (teams)

SFC	specific fuel consumption
SHF	superhigh frequency
SIGINT	signal intelligence
SIPRNET	Secret Internet Protocol Router Network
SLAM	simultaneous localization and mapping
SOC	Special Operations-Capable
SPAWAR	Space and Naval Warfare Systems Command
SRS	Standardized Robotics System
SSGN	nuclear-powered guided-missile submarine
SSN	nuclear-powered submarine
STOM	Ship-to-Objective Maneuver
TALON	one robot solution to a variety of mission requirements
TAR	tactical autonomous robot
TCA	Transformational Communications Architecture
TCDL	tactical common data link
TCO	Transformational Communications Office
TCP	Transmission Control Protocol
TCS	Tactical Control System
TDOA	time difference of arrival
TPED	task, process, exploit, disseminate
TPPU	task, post, process, use
TRL	Technology Readiness Level
TUAV	tactical unmanned aerial vehicle
UAV	unmanned aerial vehicle
UCAR	unmanned combat armed rotorcraft
UCAV	uninhabited combat air vehicle
UCAV-N	uninhabited combat air vehicle-Navy
UCS	Unmanned Control System
UGCV	Unmanned Ground Combat Vehicle (program)
UGS	unattended ground sensor
UGV	unmanned ground vehicle
UHF	ultrahigh frequency
UNITE	UAV National Industry Team
URBOT	urban robot
USAF	U.S. Air Force
USN	U.S. Navy
USV	unmanned surface vehicle
USW	undersea warfare
UUV	unmanned undersea vehicle
UXO	unexploded ordnance

VDS	variable depth sensor
VHF	very high frequency
VMS	Vehicle Management System
VSSN	*Virginia*-class submarine
VSW/SZ	Very Shallow Water/Surf Zone (program)
VTOL	vertical takeoff and landing
VTUAV	vertical-takeoff-and-landing tactical unmanned aerial vehicle
WHOI	Woods Hole Oceanographic Institution
WNW	wideband network wave form
XUV	experimental unmanned vehicle