# OPTIMIZING THE HUMAN ELEMENT IN THE AGE OF AUTONOMY[*]

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Unmanned systems (UxS) have become almost ubiquitous in U.S. military operations today, but many still wonder how they will be effectively integrated into the existing force, to succeed as a force multiplier rather than just a force enabler. As we look towards the future of UxS, we anticipate that greater autonomy will be mandated due to manning considerations, the challenge of data overload, and the need for resiliency in anti-access and area denial environments. However, as levels of autonomy are increased, it will be imperative to integrate and optimize the human element in the development and design phases, in order to maximize the capabilities of both the unmanned system and the human operator.

The human element has long been a consideration in all aspects of aviation. As the DoD moves toward increased autonomy for UxS, it is faced with identifying the proper levels of human interaction with unmanned platforms. The appropriate level of human interaction has been widely discussed when considering whether or not platforms should be armed, and whether or not decisions regarding engagement should be made by an autonomous system. While this is one aspect of the human interaction, the other, less mentioned, aspect is identifying the level of involvement that is necessary from a human factors and crew resource management standpoint. Increasing the autonomy of unmanned systems can only be done successfully if it is done in such a way that the human element remains at the center of the design.

This paper will explore the demand for increased autonomy with a movement toward manned-unmanned teaming and swarming capabilities. We will discuss the importance of the consideration of human factors and user-centered design as we work to identify the right balance of autonomy and human engagement with the system. We will also highlight examples of ground-breaking efforts currently being conducted within U.S. defense laboratories that are paving the way for achieving the goal of greater autonomy for UxS.

[*]Distribution Statement A: Approved for Public Release

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## PERSPECTIVE

"…unmanned systems are making a significant, positive impact on DoD objectives worldwide. However, the true value of these systems is not to provide a direct human replacement, but rather to extend and complement human capability by providing potentially unlimited persistent capabilities, reducing human exposure to life threatening tasks, and with proper design, reducing the high cognitive load currently placed on operators/supervisors."

*Dr. Paul Kaminski, Chairman, Defense Science Board*
*Task Force Report: The Role of Autonomy in DoD Systems*
*July, 2012*

Unmanned systems (UxS) have provided military capability to the U.S. since World War I, but their use has skyrocketed since the advent of Operations Enduring Freedom and Iraqi Freedom. During these two wars, UxS performed far more missions, in both type and quantity, than in previous conflicts. They delivered essential capabilities to the battlefield, including surveillance, reconnaissance, strike, and explosive ordnance disposal. Unmanned systems' demonstrated successes on behalf of the United States and allied forces in the Middle East and South Asia have significantly impacted the face of modern warfare. Today, UxS provide persistent capabilities, extend the warfighter's reach, and work in environments deemed too dull, dirty, or dangerous for their human counterparts. Moreover, unmanned systems boast impressive potential to transform the battlefield of tomorrow, as they are not confined by the human limitations that are imposed on manned systems.

In order to fulfill this potential, we anticipate that the continuously evolving next generation of unmanned systems will be equipped with increased levels of autonomy. Indeed, greater autonomy will become imperative due to manning considerations, the challenge of data overload, and the need for resiliency in anti-access and area denial environments. However, as levels of autonomy are increased, it is imperative to integrate and optimize the human element in the development and design phases, in order to maximize the capabilities of both the unmanned system and the human operator. Effective integration will be achieved by considering the strengths and weaknesses of both the unmanned system and the human operator. In doing so, the human element and the unmanned system will be able to effectively work together as a coordinated team, enhancing the capabilities of both man and machine.

## TAKING THE NEXT STEP: FROM "UNMANNED" TO "AUTONOMOUS"

As the use of unmanned systems has increased in recent years, so too have the calls for these systems to progress beyond remote operation towards higher levels of autonomy. The *Unmanned Systems Integrated Roadmap FY 2011-2036* outlines four levels of autonomy ranging from human operated to fully autonomous systems. Furthermore, the updated *Unmanned Systems Integrated Roadmap FY2013-2038* outlines specific near, mid, and long-term autonomy goals[1].

| Level | Name | Description |
|---|---|---|
| 1 | Human Operated | A human operator makes all decisions. The system has no autonomous control of its environment although it may have information-only responses to sensed data. |
| 2 | Human Delegated | The vehicle can perform many functions independently of human control when delegated to do so. This level encompasses automatic controls, engine controls, and other low-level automation that must be activated or deactivated by human input and must act in mutual exclusion of human operation. |
| 3 | Human Supervised | The system can perform a wide variety of activities when given top-level permissions or direction by a human. Both the human and the system can initiate behaviors based on sensed data, but the system can do so only if within the scope of its currently directed tasks. |
| 4 | Fully Autonomous | The system receives goals from humans and translates them into tasks to be performed without human interaction. A human could still enter the loop in an emergency or change the goals, although in practice there may be significant time delays before human intervention occurs. |

**Figure 1: Four Levels of Autonomy[2]**

The levels of autonomy shown in Figure 1 focus on the operation of the platform itself; however, it is important to note that increased levels of autonomy are also needed for the payload – for example, throughout the tasking, collection, processing, exploitation, and dissemination (TCPED) process. More autonomous platforms and payloads have the potential to create more effective command, control, and communications; ultimately enabling the concept that the Navy has termed "Information Dominance."[3] We anticipate that the vision of higher levels of autonomy for both platform and payload will be realized as the technology continues to advance, due to the imperatives of manning considerations, data processing requirements, and the need for resiliency in future operating environments, which are characterized by anti-access and area denial challenges.

**Manning Considerations**

Congressional researchers, military officials, and respected think-tanks are universal in their contention that the cost of military manpower makes up the largest part of the total ownership cost (TOC) of military systems across all the Services. These same officials also note that overall military manpower costs are the fastest growing accounts, even as the total number of military men and women *decrease*. In fact, military personnel expenditures have risen from $74 billion dollars in 2001 to $146 billion dollars in 2014, an increase of about 98 percent.[4]

In the current budgetary drawdown, the need to reduce these manning costs is not only pressing, it is absolutely imperative. The 2011 Budget Control Act mandated that DoD future expenditures be reduced by approximately $487 billion over the next decade.[5] The DoD recognizes that savings of this magnitude will not be possible without addressing the manpower burden. Although unmanned systems are identified as one of the few key capabilities for which funding levels were requested to be protected – and in some areas even increased – UxS manning requirements *must* decrease in order to fully realize the value of these investments.

Focusing for a moment on the U.S. Navy (the Service branch we are part of), one of the most significant ways that unmanned systems can usher in revolutionary change in tomorrow's Navy, as well as for the Navy-after-Next, is in the area of manpower reductions in the Fleet. Lessons learned throughout the development, testing, and deployment processes of most unmanned systems—especially unmanned aerial systems—demonstrate that those systems actually have sign significant manning requirements. The Air Force has estimated that the MQ-1 Predator requires a crew of about 168 personnel, while the MQ-9 Reaper requires a crew of 180, and the RQ-4 Global Hawk relies on 300 people to operate it.[6] As General Philip Breedlove, previous Vice Chief of Staff of the Air Force, has emphasized, "The number one manning problem in our Air Force is manning our unmanned platforms."[7]

Unfortunately, this technical and operational "tail" typically persists even after the system is in the field; as commanders are just as loathe to have the system fail as its developers were. There is little evidence that reducing manpower as the systems enter service is a vital part of the Key Performance Parameters (KPP) for any of these unmanned systems. This, in turn, introduces a pernicious cycle – as the unmanned systems enter service, they can require more operators, more technicians, and more "tail" than the manned systems they supplanted.

As yet, there is no broad consensus on how to define the manning requirements for UxS, how to assess what the manning requirement should be, or how it should compare to that of manned systems. However, current budget realities clearly dictate that efforts be made to reduce the current manning requirement in order to lower the TOC of these systems. This will be a crucial step towards ensuring the long-term viability of UxS' integration into the armed forces.

With the prospect of future flat or declining military budgets, the rapidly rising cost of military manpower, and the increased DOD emphasis on total ownership costs, the mandate to move beyond the "many operators, one-joystick, one-vehicle" paradigm for UxS that has existed during the past decades for most unmanned systems is clear and compelling. The DOD and the services are united in their desires to increase the autonomy of unmanned systems as a primary means of reducing manning and achieving acceptable TOC. Once sufficiently advanced, technology can help combat this manning challenge through effective teaming of manned and unmanned platforms, otherwise known as manned-unmanned teaming (MUM-T).

**The Data Overload Challenge**

Compounding the total ownership cost issue, the data-overload challenge generated by the proliferation of unmanned aircraft and their sensors has created its own set of manning issues. In fact, the situation has escalated so quickly that many doubt that hiring additional analysts will help ease the burden of sifting through thousands of hours of video. General James Cartwright, former Vice Chairman of the Joint Chiefs of Staff, has been quoted as complaining that a single Air Force Predator can collect enough video in one day to occupy 19 analysts. He stated, "Today an analyst sits there and stares at Death TV for hours on end, trying to find the single target or see something move. It's just a waste of manpower."[8]

The data overload challenge is so serious that it's widely estimated that the Navy will face a "tipping point" in the 2016 timeframe, after which the Navy's intelligence analysts will no longer be able to process or exploit the amount of data that the Navy is compiling.[9] In order to combat this problem, the Navy's Information Dominance Directorate has established a Tasking, Collection, Processing, Exploitation and Dissemination (TCPED) Working Group. This group is "actively studying Navy TCPED operations to discover a process for separating the wheat from the chaff, which should keep data transfer to a realistic level."[10] However, the ultimate success of the TCPED mission will be heavily dependent on the development of supporting C4ISR capabilities.

Rear Admiral William Leigher, the Navy's former Director of Program Integration for Information Dominance, has proposed a possible way ahead. He noted that the future of intelligence is "automated systems that can analyze and fuse enough intelligence information from multiple sources to begin to predict events."[11] Indeed, as demands for real-time intelligence, surveillance, and reconnaissance (ISR) in three dimensions continue to increase exponentially, increasing unmanned systems' capability to conduct autonomous analysis may be the only sustainable way forward.

**Resiliency in Anti-Access / Area Denial Environments**

U.S. forces have become accustomed to their ability to access regions of conflict with little difficulty; however, that access is no longer assured. According to the DoD's highest-level strategic guidance documents – including the *Joint Operational Access Concept* (JOAC) and *Air-Sea Battle: Service Collaboration to Address Anti-Access and Area Denial Challenges* – military operations in the future are much more likely to be conducted in operational environments characterized by anti-access/area denial (A2/AD) challenges.[12] Anti-access is defined as "action intended to slow deployment of friendly forces into a theater or cause forces to operate from distances farther from the focus of conflict than they would otherwise prefer."[13] The second aspect, area denial, is defined as "action intended to impede friendly operations within areas where an adversary cannot or will not prevent access."[14] In short, A2/AD limits movement into a theater as well as disrupting maneuvering capabilities within the theater.

Of note, the A2/AD threat increasingly characterizes the Asia-Pacific region, where 60 percent of Naval forces are expected to be allocated by 2020. The suite of A2/AD military capabilities there ranges from the use of kinetic weapons to non-kinetic weapons, such as cyberspace and electromagnetic spectrum operations. Indeed, a recent Air Force Scientific Advisory Board report has claimed that communications links are a "primary target of the adversary" in robotic aircraft operations.[15] Unmanned systems are currently heavily dependent upon communications and networks; in A2/AD environments where their external control is jeopardized, it becomes imperative that they are able to operate independently.

As one example, a serious vulnerability of unmanned systems' is their current level of dependence on satellites for communications and command and control (C2). Satellites are increasingly vulnerable to interference from adversaries, and the DoD is working to bolster its ability to operate in a denied environment. This challenge is particularly acute for the Navy, which must maintain the capability to operate forward in anti-access/area denied (A2/AD) regions. In the case of remotely-piloted systems such as the MQ-1 Predator and MQ-9 Reaper, if the satellite link is broken the pilot would lose direct control of the aircraft, leaving it to rely on pre-loaded software and GPS guidance. While that might be acceptable for routine missions, it presents a significant vulnerability for those missions requiring constant oversight. Overcoming this challenge will be vital to successfully ensuring that U.S. forces have freedom of access and action across all domains.

A2/AD challenges are expected to have a significant impact on all operations across all domains. However, it poses particularly hazardous challenges in aviation, as communication is essential to situational awareness for both manned and unmanned aircraft. Lost communications procedures have been successfully developed for manned aircraft. The pilot is still able to fly the aircraft until the situation is remedied or the aircraft has landed. In the case of unmanned aircraft systems (UAS), the controller will not be able to operate the aircraft if communications are degraded or lost.

Even if the data links were sufficiently robust and reliable, the current level of bandwidth demanded by UxS – especially the remotely-piloted Predator and Reaper – is quickly outpacing the DoD's supply. Insufficient availability of bandwidth has hindered the ability to distribute high-bandwidth data, such as full-motion video, which in turn has challenged DoD's ability to effectively share data across users, systems, and organizations.

The bandwidth shortfall is often made up through reliance on commercial satellite communications, which makes up nearly 80 percent of the U.S. government's satellite communications capacity.[16] However, commercial satellite communications are often not as secure as their government counterparts, and they are also extraordinarily expensive. This problem is expected to grow more severe as UxS demand for bandwidth continues to exceed the DoD's ability to field its own satellite systems.

Unmanned systems have operated successfully in the relatively permissive environment of the Middle East, but it is clear that they will require higher levels of autonomy to ensure their resilience in the contested environment of the Asia Pacific. Operating in this environment will necessitate innovation from both military and industry; however, it may also be an opportunity to take great strides towards improving unmanned systems.

The availability of communication links, the amount of data supported by these links, spectrum allocations, and resilience of systems against interference pose key challenges for the use of unmanned systems in a contested environment. Given the persistent vulnerabilities of satellite communications and the projected imbalance between supply and demand, the only sustainable way forward is to have the ability to cut the satellite "tether" that UxS currently rely on. If these systems' autonomy and interoperability were enhanced so that they were tasked with a mission but could "decide" themselves how best to accomplish it, operators could rely on the UxS onboard systems carrying out the mission rather than having to maintain direct control of the platform. Moreover, beyond ensuring their own effectiveness in the absence of satellite communications, UxS could also act as communications relays for other platforms if necessary.[17]

**DoD Demand for Increased Automation and Human-Systems Integration**

Given the vital imperatives above, it should come as no surprise that at the highest levels, DoD and DoN leadership have outlined a clear vision for advancing the state of the art of *autonomous* – not simply unmanned – systems. However, the guidance from leadership explicitly addresses the issue of human-systems integration along with autonomy. In doing so, this guidance underscores the point that as autonomy is enhanced, it will be necessary to integrate and optimize the human element in the development and design phases, in order to maximize the capabilities of both the unmanned systems and the human operator.

The recently released *2015 Office of Naval Research (ONR) Naval S&T Strategy* sets forth desired innovation and game-changing capabilities for the Navy's future force. It aligns science and technology (S&T) efforts with future Naval mission capability requirements. Autonomy and Unmanned Systems are listed as one of nine S&T focus areas in need of further alignment. Recommendations on alignment are based on higher level Naval guidance with an emphasis placed on reducing total ownership cost. The Naval S&T Strategy sets forth a vision for autonomous systems as "an integrated hybrid force of manned and unmanned systems with the ability to sense, comprehend, predict, communicate, plan, make decisions, and take collaborative action to achieve operational goals."[18]

While the Navy innovates to meet ONR's vision, it's important to note that the Navy has yet to maximize its current portfolio of unmanned systems. The 2012 Defense Science Board Task Force report *The Role of Autonomy in DoD Systems* issued a finding stating that "existing, proven autonomous capabilities are underutilized, particularly in application such as automated take-off and landing, waypoint navigation, automatic return to base upon loss of communications, and path planning."[19] Furthermore, the memorandum calls for the development of autonomy of the payload "without creating new platforms."[20]

In an effort to align and synchronize the development of efforts, the 2014 U.S. Navy Information Dominance Science & Technology Objectives (STOs) outline objectives, investments, and resources needed to meet the Chief of Naval Operation's goal to "position itself for pre-eminence in the fields of Intelligence, Cyber Warfare, Command and Control, Electronic

Warfare, and Battlespace and Knowledge Management."[21] Autonomy and Human-Systems Integration are two of the eleven technology focus areas outlined in the STOs. STO objectives for human-systems integration include the development of a user-centered design, improvement of the TCPED process, improved cognition in complex operating environments, optimized load balancing between manned and unmanned roles and capabilities and adaptive training and simulation systems.[22]

There is a clear demand for increased autonomous capabilities of unmanned systems; however, the DoD has also made it clear that this must be done with the human in mind. There is no doubt that as autonomy is further developed and integrated into unmanned systems, there will be opportunities for lessons learned and course correction. The key to successful integration of autonomy in a fiscally constrained environment is to automate key tasks that will provide the greatest return on investment and will enhance the manned-unmanned team. According to the Defense Science Board, six areas that can best benefit from increased autonomy are: perception, planning, learning, human-robot interaction, natural language understanding, and multi-agent coordination.[23]

Having some of the most in-depth experience with unmanned aircraft systems in combat, the Air Force has outlined twelve human factors issues: workload, situation awareness, vigilance, fatigue, decision making, trust in automation, information technology, field interface, onboard control interface for optionally manned vehicles, crew/operator selection and training, and manpower/manning.[24] There is a clear intersection with the Defense Science Board's recommendations for autonomy development and the issues raised by the Air Force.

The DoD and DoN are quickly moving toward the development of autonomous systems, despite being pressured by budgetary constraints. It is essential that this capability is developed affordably. Currently, the Navy and Air Force are developing UAS with ISR and strike capabilities from both land and sea. The Naval Research Advisory Committee is conducting research on the potential of uses of autonomy for the Navy and other services. The Defense Advanced Research Projects Agency (DARPA), the Air Force, Army, and Navy are all participating in S&T development programs such as DARPA's Collaborative Operations in Denied Environment (CODE) and Fast Lightweight Autonomy (FLA) programs. *The Unmanned Systems Integrated Roadmap* outlines near, mid, and long term goals that have been established to achieve this objective. While increasing the levels of autonomy is important, proper human-systems integration is equally crucial. If the human cannot manage the autonomous capabilities, the performance of unmanned systems will become sub-optimal.

**A Conceptual Model of Effective Autonomy**

If the guidance from Defense and Navy leaders above is implemented, future UxS will boast higher levels of autonomy that enable them to more effectively operate with their manned counterparts. Vice Admiral Mike Shoemaker, Commander, Naval Air Forces, has outlined a vision of future operations in which UxS serve as the "wingman" to manned aircraft.[25] In his model, UxS are complementary to, vice a replacement of, piloted aircraft. He explained that this conceptual model is crucial to the Navy's success moving forward, as it "allows for a flexible, lethal, and capable force." The art of integrated manned and unmanned platforms has been termed "manned-unmanned teaming" (MUM-T).

MUM-T is intended to utilize the strengths of both manned and unmanned platforms to achieve what is unachievable with only one platform. MUM-T combines unmanned systems with the warfighter to achieve enhanced situational awareness, greater lethality, improved survivability, and sustainment.[26] Early stages of MUM-T are currently being achieved. The

Navy plans to pair the Triton with versions of the P-8 Poseidon and the Fire Scout with the MH-60 Seahawk. Although details on the Unmanned Carrier-Launched Airborne Surveillance and Strike (UCLASS) remain forthcoming, the Unmanned Combat Air System Demonstrator (UCAS-D) has already achieved historic teaming milestones. On August 17, 2014, an F/A-18 and UCAS-D made aviation history by completing a planned formation flight around an aircraft carrier. The U.S. Army has also achieved notable accomplishments as they have done a great deal of work teaming an MQ-1C Gray Eagle with an AH-64 Apache.

MUM-T will become increasingly necessary, particularly as the U.S. rebalances toward the Asia-Pacific region. This will provide additional protection to our troops, increased situational awareness, and it will allow us to operate with a smaller and more agile force. MUM-T will also allow us greater flexibility and agility when faced with an A2/AD environment. As we design for MUM-T capabilities, the consideration for the human element and human-system interface is imperative. If the human is intended to be able to take over full control of the vehicle, consideration must be made to avoid removing the human too far out-of-the-loop where decision making, situational awareness, and successful and safe operation can be degraded or lost completely.

Autonomy will play a key role in the innovation of unmanned systems. If done correctly, it will serve as an enabler which will address some of the manning considerations, the challenge of data overload, and the need for resiliency in anti-access and area denial environments. At some point, the unmanned system, and the data collected by the system, will interface with a human. Therefore, in order to realize the full potential of unmanned systems, we must optimize both the unmanned system and the human operator by placing a greater emphasis on human factors engineering and human systems integration.

## THE WAY AHEAD: INSTANTIATING HUMAN-SYSTEMS INTEGRATION

Due to urgent operational needs during the conflicts in Iraq and Afghanistan, UAS were subjected to a rapid acquisition process, bypassing acquisition milestones in order to field the UAS in theatre. In many cases, prototype or developmental systems were fielded. While unmanned systems have existed for decades, this generation of unmanned systems were initially developed and fielded without the proper consideration of human-system integration and training. This technology was truly disruptive. Although urgent operational needs were understandable, and were met, long-term ramifications quickly became apparent. Operations, training, maintenance, and logistics all needed to be reconsidered; however, the needs of the battlefield remained of the utmost importance. Despite all of this, the ingenuity of the warfighter prevailed and ensured the successful operation of these systems in unique and unanticipated ways. Systems that were originally intended for ISR were also used for the detection of improvised explosive devices (IEDs), force protection, and the pursuit of high value targets.[27] However, the message from the warfighter was clear – the human-system interface had more than enough room for improvement. As the operational requirements of the conflicts in the Middle-East begin to subside, the Navy has an opportunity to take a step back and evaluate how it plans to integrate unmanned systems into fleet operations, while incorporating the lessons learned across the services from the past two decades.

### Human Factors

"Human factors is a scientific, theoretical, and applied discipline dealing with psychological, physical, and organizational aspects of the interaction between humans and systems – primarily in occupational contexts."[28] Human factors engineering has long been an important consideration within the aviation industry. The successful safety record enjoyed by the industry is the result of years of research and continued focus on the safe and effective integration of the human element in the aircraft. Human factors considerations were essential in the integration of the glass cockpit in commercial, military, and civilian aircraft. Human factors not only apply to the pilot, but also to the flight crew, maintenance crew, airline and airport crew and employees, and air traffic control. The study of human factors has expanded to include industries that rely on optimized interaction between man and machine such as the medical, nuclear power, and maritime industries. As computerized systems are rapidly becoming used across a variety of systems in multiple domains, involving multiple groups of people, human factors engineering and human-system integration are becoming more widely used today.

Human factors is essential for successful use of unmanned systems because despite their name; the human is most certainly a part of the overall "system." Whether it's controlling the system, observing the system, or analyzing data, there will be a touch point with human counterparts. Although unmanned systems have presented quantifiable benefits to military forces, as we continue to place an emphasis on increasing the levels of autonomy, it is crucial that human factors considerations are made in the design of these autonomous capabilities in order to maximize the potential of both the human and the machine.

***Human Reliability and Performance***

Unmanned systems consist of two major parts; the platform and the payload. Much of the focus has been primarily placed on the development of the platform; the development of the payload has been given a secondary focus. Focus on the development of the payload is equally, if not more, important as the payload provides the critical capabilities, while the platform is the method of transportation of these capabilities. There are multiple people involved in the operation of the UxS; platform operators, sensor operators, mission commanders, and imagery analysts, all working together toward a common goal. While it is possible for machine responses to vary unexpectedly, it is easier for developers to ensure hardware reliability than it is to control or ensure human reliability, especially given the number of individuals involved with each system. Human responses to stimuli can vary by situation, by day, and by individual; and are far less predictable. Humans are susceptible to a variety of failure modes.

Human performance is derived from a combination of aptitude, training, and motivation.[29] It is difficult to predict how long one person may perform at a high level until they exceed their maximum capacity, at which point performance is rapidly degraded. Highly motivated individuals may perform at a higher level than people with aptitude and training but have a lack in motivation. Once the effect of stress and workload is applied, the human responds to both physiological and psychological effects and becomes even less reliable. Compounded stress, duration of stress, fatigue, illness, training, motivation, and environment are among other factors that also affect the human element and reliability and failure modes.

Additional failure modes that pose significant challenges for the successful operation of UxS are boredom, lack of vigilance, stereotypes, perception, and coupling.[30] Tasks that require long durations of vigilance, or become boring, require high levels of concentration. Typically, human performance is degraded in situations when there is little stimuli or feedback. This is an issue seen by imagery analysts who review hours on end of "death TV." However, the inability to keep focus may result in human error. Automating tasks that can be considered as dull would reduce the amount of human error; however, it may then introduce unforeseen machine error.

Stereotypes present a different type of problem. Humans become accustomed to how things operate; for example, screws typically tighten to the right and loosen to the left. This becomes habitual and the human responds accordingly without taking time for additional thought about how to loosen or tighten a screw. However, if the stereotype is changed unexpectedly, or tasks are presented in a different order, it can cause confusion and create unintended chaos that can rapidly result in human error. Sometimes what is sound to the engineer can wreak havoc for the user.

Perception is perhaps one of the more difficult failure modes to contend with as a person's perception is the result of their individual background. The term "perception is reality" depicts how critical perception can be when designing unmanned systems. When an operator must rely on the output of the system for situational awareness, perception is critical, because the operator is physically removed from the location and relies on this information to make tactical decisions. It is important that the operator's perception of the display is truly reflective of the environment.

Finally, coupling is a failure mode which is the result of two or more unrelated situations or events taking place that the operator mentally links together. This phenomenon leads the user to make misinformed decisions based on an unintended linkage, and the results can be disastrous. The potential for human failure modes can occur in nearly any situation, in any environment. However, designing UxS and their corresponding control stations accordingly can help mitigate these factors.

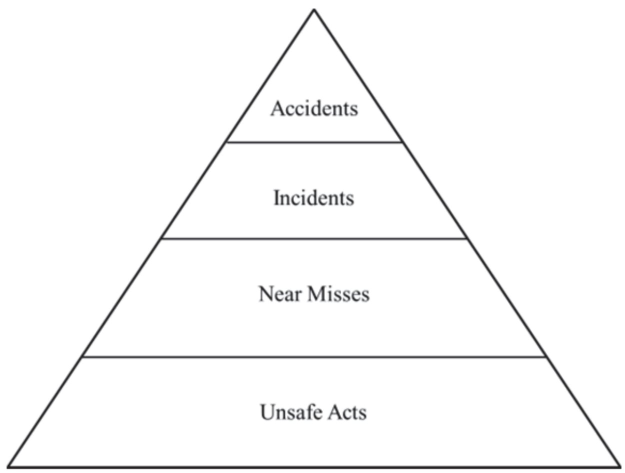



**Figure 2: Iceberg Model**[31]

Human error is cited as a causal factor in accidents across all industries and all domains. It is commonly found that regardless of domain or industry, one accident, or mishap, is similar to the tip of an iceberg. There are undoubtedly an exponentially larger number of incidents, near misses, and unsafe acts than are actually discovered or reported (Figure 2).[32] Specific ratios vary by industry; however there is consistent evidence the pattern of practicing unsafe procedures as part of a regular routine will ultimately lead to near misses, incidents, and ultimately an accident. In many cases, the design of the system contributed to, or caused the human error.

Although human error is so often found to be the cause of an accident, it is surprisingly difficult to develop a consistent solution because the human response can be an unpredictable variable. At best, we can work to mitigate the problem by instilling adequate design, training, and selection of the right individuals for the job. Sidney Deckker outlines a "new view" of human error involving the following three factors:[33]

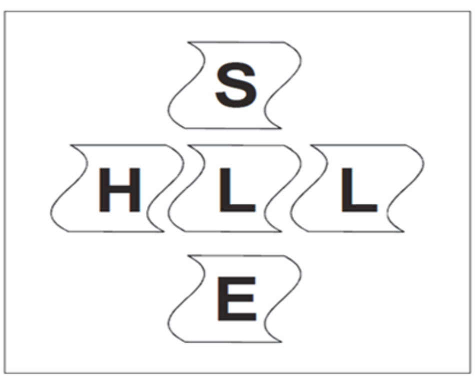
- Human error is not a cause of failure. It is the effect, or symptom, of deeper trouble.

- Human error is not random. It is systemically connected to features of people's tools, tasks, and operating environment.
- Human error is not the conclusion of an investigation. It is the starting point.[34]

As technology continues to evolve, the need for human factors considerations continues to grow. Despite the complexity of the system, the human must find the system usable or the benefits of the system may be lost. In the case of unmanned systems in the military this becomes even more important as the human element is a warfighter using the systems to gather information, secure an area, or strike a target, these systems provide the military, with unprecedented reach. Over time, industries have developed several human factors models to depict the relationship between human and machine. The Software, Hardware, Environment, and Liveware (SHEL) Model and the Sociotechnical Model display how consideration for human factors has evolved. Optimizing the relationship between the human and machine is the desire of the military and the crux of human factors engineering; placing the human element at the center of the design of the system.

***The Software, Hardware, Environment, and Liveware (SHEL) Model***

Developed in the 1970s-1980s, the "SHEL" Model was most notably used by the International Civil Aviation Organization (ICAO). ICAO, like the Federal Aviation Administration (FAA), is largely responsible for aviation safety on a global scale. The SHEL model is also known to be used across the maritime domain. The SHEL model consists of four elements: software (S), hardware (H), environment (E), and liveware (L). Each element fits together in the model. This model illustrates the relationship between different system components. As you can see in the figure below, liveware is mentioned twice in the model. The liveware referenced at the center of the diagram represents the operator, while the liveware to the right represents other stakeholders that interact with the operator.




| SHEL Element Definitions | |
|---|---|
| Software | Procedures, training, and support |
| Hardware | Machines and equipment (technology) |
| Environment | The environment in which the software, hardware, and liveware exist |
| Liveware | The human element |

**Figure 3: SHEL Model and Element Definitions**[35]

The definitions of the SHEL Model and SHEL element definitions are noted in Figure 3. The liveware, or human element, is in the center and is affected by each of the other elements. While the human element is noted as being "remarkably adaptable," the wavy edges of each element reflect the fact that humans are not standardized in the way that hardware is. Irregularities exist which can hinder human interaction and performance within the combination of elements. These irregularities, or human factors, must be understood in order to design a system that can successfully be operated by a human while avoiding any additional undue stressors which may add one more link to the accident chain.

Although the idea of behind this concept is sound, it quickly becomes apparent why this model has become obsolete. The relationships between the SHEL Model elements become prevalent when two elements are combined. For example, liveware-hardware (L-H) represents the interface between the human and machine (noted as technology). Liveware-software (L-S) discusses the interface between the human and the "software." Software, in this case, is noted as procedures, training and support, as opposed to the modern meaning of software as it is known today. Liveware-liveware (L-L) addresses the relationship between the operator and other members within the team or work environment who are working together to accomplish a common goal. Finally, the relationship between liveware and the environment (L-E) includes the impact the environment has on the performance of the human element. [36]

The SHEL Model was revolutionary in that it visually depicted and discussed how the human's integration into the system could positively or negatively affect performance. This particular model states that "a mismatch between the liveware and other four components contributes to human error. Thus, these interactions must be assessed and considered in all sectors of the aviation system,"[37] or arguably any system.

***Sociotechnical System Model***

Although the SHEL model is widely used, ironically, one of the main criticisms of the model is the interpretation of the concepts. The context of the use of software, hardware, and liveware, in the SHEL model can be miscommunicated and misunderstood. At the time of development (1970-1980) software and hardware had different meanings than they do today. Many models exist for various industries; the Sociotechnical System Model in particular provides a visual depiction of the interrelationships between the different elements. When comparing the SHEL model to the Sociotechnical System Model, it is clear that human factors studies continue to evolve with technology. The Sociotechnical System Model depicts the linkage between a series of concepts and indicates how factors interact and impact system performance.

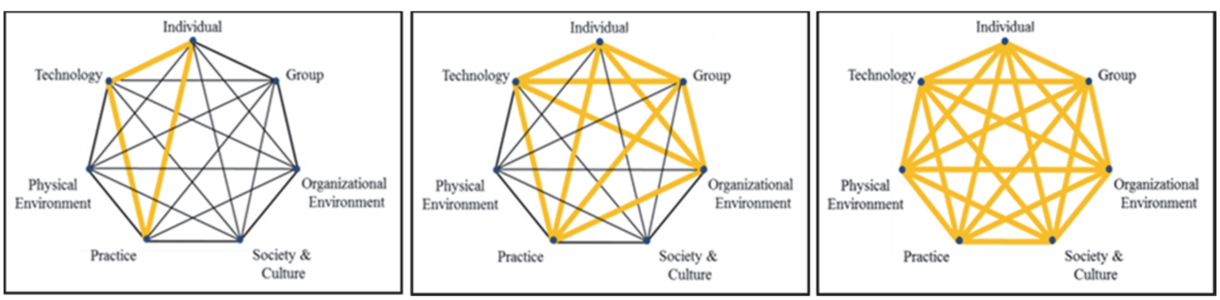



**FIGURE 4: Sociotechnical Systems Model[38]**

As noted in Figure 4, the Sociotechnical Systems Model is comprised of seven elements: individual, practice, technology, group, physical environment, organizational environment, and society and culture.

**Table 1: Sociotechnical Systems Model Element Definitions**

| Sociotechnical Systems Model Element Definitions[39] | |
|---|---|
| Individual | Human component – physical limitations, sensory limitations, psychological limitations, physiology, workload management, skill, and experience |
| Group | Relational and communication aspects – communication, interactions, training, supervision, and regulatory activities |
| Organizational Environment | Company and management – procedures, instructions, policies, and rules |
| Society and Culture | Sociopolitical and economic environment of which the organization exists |
| Practice | Informal rules and customs (not procedures/instructions) |
| Physical Environment | Physical work environment – temperature, air quality, lighting, visibility, vibration, noise, anthropometry |
| Technology | Human-hardware interface, human-software interface, automation, equipment, vehicles, tools, and manuals |

The definitions of each element of the Sociotechnical Systems Model are outlined in Table 1. With this model, the interrelationships between each element are visually depicted. Although all elements are present, given any particular situation, some may be more prevalent than others. For example, an individual operating a UAS may be concerned with the individual, practice, and technology elements for part of the mission, and later rely on the individual, technology, group, practice, and organizational environment for another. Although one or more element may be the most pressing, each of the elements are ever-present, and are always a factor to some extent. Each element also has its respective limitations which must be understood, and addressed, in systems design.

The commonality in both of these models, as well as other models used across other industries, is that great consideration must be given to the multitude of touch points that exist between unmanned systems and humans. Considering the human element in the early stages of the design process increases the likelihood that the system will fit with a human operator rather than vice versa. Regardless of the model or terminology used, human factors are the consideration of the human element and its fit within the surrounding environment. Considering the human element in the early stages of the design process increases the likelihood that the system will fit the human element rather than vice versa. As we move further into an environment where single operators are expected to control multiple platforms and the amount of data continues to increase, it is important to remember that these systems are designed to increase situational awareness, complete surveillance, provide data to enhance decision making abilities, protect U.S. and allied forces, and strike designated targets. These capabilities were intended to optimize the human's ability to prevent or win a conflict. "If the human factor is taken into account, a tight fit between person and design can be achieved and the technology is more likely to fulfill its intended purpose."[40]

## Optimizing the Human Element

The demands of the conflicts of the past 10 years have resulted in the integration of UAS into the military at a much more rapid pace than predicted. They were quickly placed into the rapid acquisition process where the main goal was to field the systems on the battlefield. While this process met short term goals, rapid fielding has created long term unintended consequences. UAS were fielded without a formal CONOPS. Manning and maintenance requirements were unknown and underestimated. Test and evaluation was limited. Spare parts and logistics support were often unavailable or sparse at best. The necessary bandwidth to process and disseminate data was unavailable. Training was more or less done on the job to meet the demands of the battlefield. Each of these implications affected the warfighter as they resulted in an inefficient and less effective method of manning these systems. The Defense Science Board states that "no unmanned, autonomous systems have formally completed operational test and evaluation prior to being released to the field. Rather, urgent needs have focused deployment of prototype or developmental systems before completing all acquisition milestones."[41]

The Defense Science Board has issued several recommendations on the integration of greater autonomy; many of which include the consideration of the human element. Human-systems interface recommendations are as follows:[42]

- Abandon the debate over definitions of levels of autonomy and embrace a three-facet (cognitive echelon, mission timeline, human-machine system trade spaces) autonomous system framework. This framework would focus on the allocation of cognitive functions and responsibilities between the human and computer.
- Structure autonomous systems acquisition programs to separate the autonomy software from the vehicle platform.
- Create developmental and operational test and evaluation techniques that focus on the unique challenges of autonomy.
- Include lessons learned from using autonomous systems in the recent conflicts into professional military education, war games, exercises, and operational training.
- Work with the Services to create a coordinated S&T program to strengthen enabling autonomy technologies such as perceptual processing, planning, learning, human-robot interaction, natural language understanding, and multi-agent coordination. Emphasis should be placed on user interfaces and "trusted" human-system collaboration, perception and situational awareness in a complex battlespace, and large-scale teaming of manned and unmanned systems.

While some fear the perception that unmanned systems will eventually operate similar to that of a 21st-centruy "HAL", turn on its masters and operate beyond our control, in reality, humans are and always will be <u>part</u> of the unmanned system. While platform capabilities will likely advance to a state where fully autonomous operation is possible, the question whether or not this is morally ethical in military operations remains to be seen. At the recent Control Architecture for Robotic Agent Command and Sensing (CARACaS) demonstration, Rear Admiral Matthew Klunder states "we still believe that there should be a human that makes that decision."[43]

> Instead of viewing autonomy as an intrinsic property of unmanned systems in isolation, the design and operation of unmanned systems needs to be considered in terms of human-systems collaboration…A key challenge for operators is maintaining the human-machine collaboration needed to execute their mission, which is frequently handicapped by poor design. A key challenge facing unmanned systems developers is the move from a hardware-oriented, vehicle-centric development and acquisition process to one that emphasizes the primacy of software in creating autonomy.[44]

## CURRENT RESEARCH AND DEVELOPMENT INITIATIVES

SPAWAR Systems Center Pacific is the Nation's only full-spectrum C4ISR laboratory providing research, development, acquisition, test-evaluation, and full life-cycle support across systems that integrates warriors, sensors, networks, command-and-control platforms and weapons into a fully netted combat force. With over 50 years of established leadership in the development of secure, networked, collaborative unmanned and autonomous systems, SSC Pacific is at the forefront of turning ideas and concepts into operational capabilities. The Center is making strides to further the development of autonomous systems by addressing human-systems integration issues early in the design process. SSC Pacific has teams striving to develop solid requirements for the appropriate and effective human-system integration for the supervisory control of multiple autonomous systems. The Center also has teams developing evolutionary concepts for autonomous systems including a heterogeneous system capable of operating in multiple domains.

**Research Environment for Supervisory Control of Heterogeneous Unmanned Vehicles Simulator (RESCHU SP)**

As we've noted, the military services are united in their desire for UxS featuring higher levels of autonomy. However, the services don't currently have a rigorous method to assess what level of autonomy is required, or which components should be autonomous and which should remain human operated. In addition to this need to better assess the requirement, as C2 architecture evolves toward one operator controlling multiple unmanned systems, it is important to consider the amount of information that the operator will be subjected to in comparison to the already overwhelming amount of data used in today's standards. Increased autonomy will alleviate this overload; however, several design challenges must be addressed. Human limitations, role allocation, levels of automation, and human-machine communication requirements must be effectively defined if the human element is to provide adequate supervisory control of one or more unmanned systems. Each of these variables must be determined and understood within new scenario requirements in order to design effective command and control systems and technologies that will enhance human performance in these complex environments. Workload, the level of cognitive capacity, overload, complacency, and level of vigilance must be considered as they are essential to providing the appropriate level of situational awareness to the operator. [45]

In order to adequately evaluate design challenges and establish requirements for human performance for the design of effective autonomous systems, SSC Pacific and the Office of Naval Research (ONR) have developed a simulator that addresses supervisory control of multiple unmanned systems while allowing flexible manipulation of experimental variables. The initial version of RESCHU was developed by the Massachusetts Institute of Technology (MIT) as a Java-based simulator that allowed supervision of unmanned aircraft and unmanned undersea vehicles completing surveillance related tasks. SPAWAR SSC Pacific modified this simulator in order to integrate the complexities of futuristic Naval missions. The SPAWAR version of RESCHU was named RESCHU SP. RESCHU SP includes a reorganized code structure to support the manipulation of experimental variables, the availability of a wide range of experimental manipulations, and the representation of a more complex Naval environment.

RESCHU SP's Naval scenario includes an asset to protect, a variety of unmanned platforms representing blue forces to coordinate for protection, and an array of red forces for interrogation, target, and potential attack. Developers also added mission definition language as well as a heterogeneous team made up of unmanned air vehicles, unmanned surface vehicles, and unmanned undersea vehicles.[46] In this version, the asset requiring protection is an oil rig. A single operator is able to control multiple unmanned vehicles to identify and destroy enemy contacts that are attacking the oil rig.

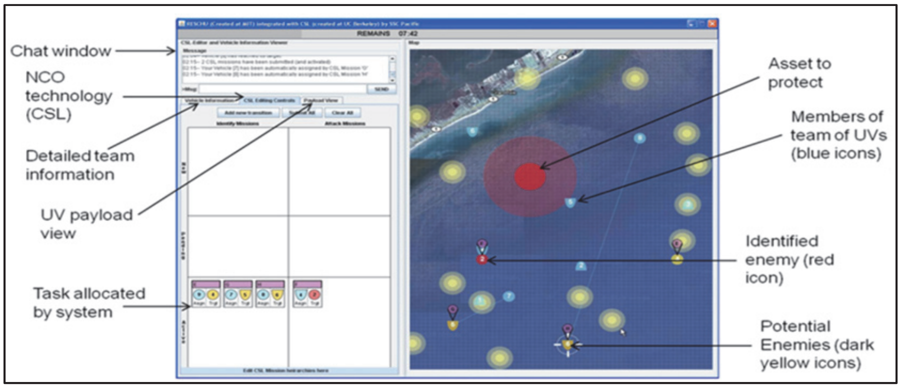



**Figure 5: RESCHU SP Interface**[47]

The RESCHU SP interface, as seen in Figure 5, consists of two windows, laid out side-by-side. The window on the right reflects a geo-situational display depicting the spatial orientation of the protected asset, the location of both blue and red forces, and the identification of any specified hazard areas. The window on the left is a panel that displays vehicle information, the Collaborative Sensing Language (CSL) editing controls, and the payload view. Developed by the University of California, Berkeley, the CSL is a mission definition language that assigns identification and targeting tasks. The CSL completes low-level decision making while it identifies and designates high-level decision making to the operator for handling. SSC Pacific adapted the original version of CSL to include a mission scenario with multiple heterogeneous vehicles.[48]

In this example, the operator assigns tasks (identification or attack) to the CSL system. The system then uses an optimization algorithm to identify which vehicle or vehicles are appropriate for each individual task. Operator tasks also include the prioritization and submission of tasks within the CSL, engagement of both the video payload and target system, analysis of video payload to identify whether an unknown vehicle is a friend or foe, engagement to attack red force contacts, and hazard area avoidance.

As the operator works through the simulation, a script is captured which is used to calculate quantitative and qualitative performance data from each human-in-the-loop experimentation trail and allow evaluation of human-machine performance. The script contains detailed information about the movement and states of both the operator and the automated server which can be stored and used for further analysis. Quantitative measures obtained include the flow of tasks between the human and machine, wait times, service time, neglect time, and load time. Qualitative measures include damage status, time to achieve tasks, and number of hits to target. RESCHU SP now has a video feature which can mimic a weak link or lost communications by degrading or freezing the image on the screen. This can be done with a level of uncertainty in order to capture realistic human responses to the situation.[49]

There are four element types that define the scenario file; vehicles, vital assets, game events, and game settings. Each element has its own validation requirements, variables, and range of acceptable values.[50] The scenario file allows scientists to specify the scenario requirements without the need of modifying the source code and having programming skills. This new scenario file is called from the configuration file and a new scenario is launched. The configuration file allows manipulation of the scenario file, simulation mode (i.e. experiment and administrator), and surveys (i.e. entry and exit).

This simulator capability allows scientists to easily manipulate variables such as asset numbers, locations, protection areas, team and enemy vehicle capabilities (i.e. UxV type, speed, payload, and initial location), friendly vehicle detection, rate and size of hazard areas, task arrival rate, uncertainty (i.e. vehicle and communication link reliability) map display, and mission time. These features allow the simulator to be highly-flexible, allowing a wide range of experiments to begin to define how the human performs within different scenarios (i.e. workload and team size).

SSC Pacific is currently working toward converting content into individual widgets to allow for easy manipulation of the interface structure and easier modifications to the individual components. Moreover, the new simulator version will allow for the manipulation of different levels of automation, the manipulation of the level of uncertainty, an open street map capability that will tie vehicles, assets and hazard areas to real map coordinates, and a database for easier evaluation and analysis of performance measures.

RESCHU SP is intended to capture data that will be helpful in ultimately defining tangible requirements for human-system integration with autonomous systems. The type of data collected within this simulation will be invaluable in ensuring that the platform, the payload, and the human element effectively work together as a coordinated team. This is how we will optimize the relationship between man and machine and achieve the untapped potential of these systems.

**Heterogeneous Autonomous Mobile Maritime Expeditionary Robots (HAMMER)**

The Navy has expressed its desire for increased autonomy, the operation of multiple unmanned systems per operator, and the development of novel platforms. Until recently, the development of one heterogeneous system combining an unmanned surface vehicle, unmanned aerial vehicle, and an unmanned undersea vehicle had been a vision for the future. SSC Pacific is working on groundbreaking research on the development of Heterogeneous Autonomous Mobile Maritime Expeditionary Robots (HAMMER). Over the next three to five years, the Center for Innovative Naval Technologies-Information Dominance (CINT-ID) Heterogeneous Autonomous Mobile Maritime Expeditionary Robots (HAMMER) project, funded by Office of Naval Research (ONR), aims to successfully integrate unmanned surface, aerial, and underwater vehicles.

SSC Pacific's focus is to create a platform where one operator is able to control multiple unmanned systems. The HAMMER platform is heterogeneous as it consists of an unmanned aerial vehicle, an unmanned surface vehicle, and an unmanned undersea vehicle, all designed to operate together as one autonomous integrated system which creates a comprehensive C4ISR system that can be used across multiple domains. A Wave Adaptive Modular Vessel (WAM-V) catamaran is used as the central node and main transport mechanism capable of carrying unmanned aerial vehicles and unmanned undersea vehicles distances over 100 miles.[51]

The particular WAM-V used in the HAMMER project was purchased without a propulsion system, power, or sensor attachments. This type of simple structure allows for an exceptional experimental platform. The propulsion system was designed to have two "pod-like" cylindrical cases to extend the hull shape. The pods serve as the attachment location for the motors, as well as a storage contained for batteries and electronics. The pods are designed to carry 155 pounds of payload and are attached to the WAM-V by an adjustable hinge plate, which also improves the stability of the vehicle.


**Figure 6: (left) WAM-V USV on a test mission, (right) a group of maritime UxSs**

In order to provide power to the multi-platform system, a Range Extender was implemented as the central power source. The Range Extender is a hybrid power system that uses a combination of Lithium-Ion batteries, solar panels, a diesel generator, and other alternative energy harvesters. The Lithium-Ion batteries provide a total of 7,200 Watt-hours. The diesel generator will recharge the batteries and provide power to the system when the batteries become depleted. The onboard CPU controls and manages the generator and decides when to switch from battery to generator power. Continuously charging and discharging the batteries increases the range by at least 50 miles, depending on the mission.[52]

The WAM-V is currently being outfitted with sensors crucial to the system's functionality as well as a payload of sensors to accommodate a specific mission. An Inertial Measurement Unit (IMU) and Global Positioning System (GPS) are typically needed for navigation onboard most robotic platforms. While Light Detection and Ranging (LIDAR) can be used as both a navigation sensor and mission payload in a GPS denied environment. The LIDAR will be used to map the environment above the surface while localizing the WAM-V within the map. Complex mapping below the surface will be provided by sonar. Ultimately, these maps will be fused to provide increased situational awareness. A stereo camera is another mission payload that will be used to classify, identify, and track objects in the area. Sensors can be either installed directly on the platform or attached to a gimbal-pole system that can be lowered into the water.[53]

In response to the Naval and DoD strategic guidance demanding increased autonomy and human-system integration, SSC Pacific has been working on several initiatives to make this possible. Distributed Control of Unmanned Systems Using Widgets, Multi-Robot Operator Control Unit (MOCU), and the Intelligence Carry-on Program (ICOP) are examples of SSC Pacific's work in this area. When designing the human-interface to the HAMMER system, the concepts of these programs were considered. A prototype was developed which models how the final graphical user interface (GUI) will be designed. The GUI is designed so that a user unfamiliar with the system will be able to quickly and easily learn how to operate the system, resulting in a reduction in training time. Human-system integration has been a consideration since the inception of this project as it will be a critical component to the successful operation of a team of heterogeneous unmanned systems.[54]

The WAM-V is accompanied by both an underwater and aerial vehicle. Together, this system will fuse sensor and user information to perform missions in a variety of environments. The unmanned aerial system (UAS) consists of the aerial vehicle, mission payload, and onboard sensors and equipment. The UAS is a helicopter with an autopilot and the availability for a ten pound payload. Current research is focused on core tasks such as takeoff and landing; however requirements for the UAS specify a flight time of 45-60 minutes with operation in various weather and sea-states. The integration of the unmanned undersea vehicle is planned in future years along with the development of the overarching communications framework. Once complete, HAMMER will achieve heterogeneous system autonomy.[55]

## CONCLUSION

As the DoD rebalances towards the Asia Pacific and focuses on implementing greater autonomous capabilities and continued innovation, designing with the human in mind will be critical for success on the battlefield and maintaining military superiority. For the most part, the human-machine interface has been an afterthought and as a result, existing capabilities have been underutilized.[56] The TCPED process is highlighted by the Air Force and the DoD as an area that is in dire need of automation. Real-time intelligence is critical to the successful operation in any military environment; however as we move to an even more dynamic and evolving battlefield of the future, this capability is absolutely essential. In a fiscal environment where we continue to do more with less, capability investments must be utilized to the fullest extent. The movement toward increasing autonomy must be done in a way to maximize capability and optimize the strengths of both human and machine.

"Perhaps the most important message for commanders is that all systems are supervised by humans to some degree, and the best capabilities result from the coordination and collaboration of humans and machines."[57]

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