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UAV Software Architecture

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This paper will explore software architectures in Unmanned Air Vehicle (UAV) systems. It is an expanded chronological literature survey of publicly available literature on the topic of software architecture issues faced by designers of UAV systems. Focus is mainly on command and control software but intelligence, surveillance and reconnaissance software architecture differences will also be explored. The intent is to show how UAV software architecture evolved to its current state. It starts with early development of the technical software architecture discipline and ends with current UAV software issues of interoperability, commonality, video compression techniques, etc. Examples of literature being reviewed include *Software Architecture: Perspectives on an Emerging Discipline,* Garlan, D. and Shaw, M. (1996)[1]; *Birds of Prey, Predators, Reapers and America's Newest UAVs* in Combat, Yenne, W. (2010)[2]; *Software-Enabled Control, Information Technology for Dynamical Systems,* edited by Samad, T. and Bala, G. (2003)[3]; "A Distributed Architecture for Autonomous Unmanned Aerial Vehicle Experimentation," Doherty, P., Haslum P., Heintz, F., Merz, T., Nyblom, P., Persson, T., and Wingman, B., (2004)[4]; "Intelligent Systems Software for Unmanned Air Vehicles," Sinsley, G., Long, L., Niessner, A., and Horn, J. (2008)[5] and *Unmanned Rotorcraft Systems*, Cai, G., Chen, B., and Lee, T. (2011)[6]. Current UAV open software architecture programs and platforms such as the Predator, Global Hawk, and Pegasus will be investigated and compared. A full bibliography is included after Appendix A.

I. Introduction

"An architecture can be defined as the structure of components, their relationships, and the principles and guidelines governing their design and evolution over time. In simple terms, an architecture is an in-depth blueprint for constructing and integrating all aspects of a software-intensive system."[7] It also has been described as a strategic design of how a solution is implemented (e.g., component based engineering standards, security) and a functional design of what a solution does (e.g., algorithms, design patterns, low level implementation).

In 1996 Garlan and Shaw wrote in *Software Architecture:Perspectives on an Emerging Discipline*[1] that architectural issues include organization of a system as a composition of components; global control structures; protocols of communication; synchronization and data access, etc. They observed common patterns for systems organizations used by software developers that included data flow systems, call-and-return systems, virtual machines, data-centered systems (databases), distributed processes, and domain-specific software architectures. Deciding on the most appropriate architecture for a given problem or domain was and still is an ongoing challenge. Garlan and Shaw show how to construct a design space for alternative architectures and create design rules to choose an applicable system design based on functional requirements.

Garlan and Shaw listed the basic design requirements for mobile robotics as: (1) deliberative and reactive behavior, (2) allow for uncertainty, (3) account for dangers, and (4) flexibility. With respect to these requirements they evaluated the four architectures used for mobile robotics shown in Figure 1 which are control loop, layers, implicit invocation, and blackboard. The Closed Control Loop solution was recommended for simple robotic systems that do not deal with complex external events. The Layered Architecture approach organizes the components very appropriately but may react too slow in dealing with external events in a real-time environment. The third solution implicit invocation used in Task Control Architecture (TCA) is structured around event handling.

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TCA is recommended for more complex robotic projects and has been used for numerous mobile robots. TCA provides a complete set of coordinating tasks and provisions for performance, fault tolerance, safety and concurrency. The TCA Architecture consists of a hierarchy of tasks or task trees. There are many operations for dynamic reconfiguration of task trees at run time in response to changing environmental conditions and robot state. The fourth solution is a Blackboard Architecture which consists of a central Blackboard or database for receiving and sending commands, sharing data and resolving conflicts. It supports concurrency and has exception handlers for dealing with uncertainty.

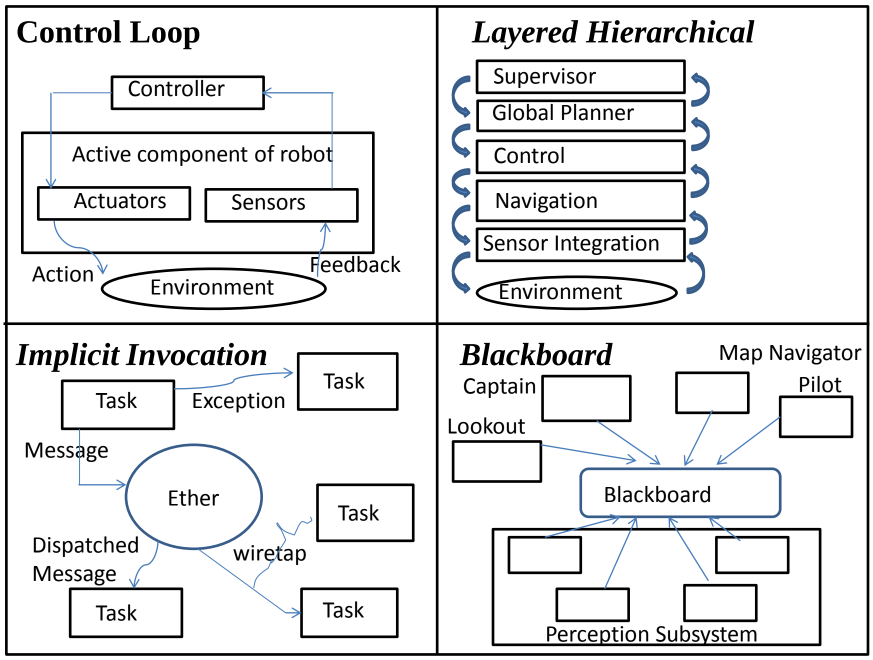

Figure 1. Mobile Robotics Architecture Types (1996)[1]

II. Early UAVs

The early UAVs developed by radio-controlled (RC) technology did not have a software architecture. During World War II several experimental unmanned aircraft were built and tested for aerial torpedoes with up to a 100 mile range. After World War II these experimental aircraft continued to develop in the RC aircraft hobby field. The RC aircraft were the backbone of modern UAVs. Around 1940 RC aircraft were developed into RC aerial target aircraft (and later as observation platforms) used by the U.S. Army Air Forces (USAAF).[2]

The first generation of military unmanned aerial vehicles ranged from 8 feet (ft) 8 inches (in). to 9 ft. 3 in. in length with wingspans from 12 ft. 3 in. to 11 ft. 6 in. Their speed increased from 85 miles per hour (mph) to 140 mph and endurance was about one hour. As can be seen in Table 1 in Appendix A, the OQ-1, developed by Radioplane (acquired by Northrop Corporation 1952), was the first radio-controlled aerial target drone (and later reconnaissance) acquired by USAAF in 1940.

In the 1960s the U.S. Air Force (USAF) began using Firebees and Lightning Bugs, America's longest flying RC aircraft in reconnaissance roles. UAVs in the 20th century where mainly used for aerial target drones and reconnaissance. The AQM-34L Lightning Bug was a precursor to the 21st century UAV and used real-time television imagery. It was experimentally fitted with electronic radar jammers and AN/ALE-38 chaff dispensers. In 1995, USAF stood up the first UAV Squadron, the 11th Reconnaissance Squadron, at Indian Springs Auxiliary Airfield (Creech Air Force base (AFB)) in Nevada.[2]

During the Cold War in the 1970s and 1980s there was little interest in UAVs. Satellite capabilities then increased dramatically and by the mid-1990s the UAVs were an integral part of the battlefield.

III. Modern UAVs

A. 21st Century First Generation UAVs[2]

UAVs around the turn of the century benefited not only by increases in satellite capabilities but also by technology advances in computer processing power, algorithm development, use of real-time systems, electromechanical flight control systems, vision/radar systems, navigation systems, and weapons system integration computers. All of these first generation capabilities affected software architecture development.

First generation UAVs in the 21st century where initially used by U.S. Department of Defense (DOD) as aerial target drones and for reconnaissance missions. The UAV role was expanded to include long range strategic missions and eventually strike missions. As a result of the expanded mission set, in 1997 the DOD readopted the "Q" as a primary UAV designator for the long range strategic and strike missions.

The Northrop Grumman RQ-4 Global Hawk used in the long endurance reconnaissance role was the largest UAV to be flown by the military at the turn of the century. It had a length of 44 ft., wing span of 116 ft., and gross weight of 25,600 lbs. The General Atomics Predator was also used in the reconnaissance role and was equipped with Northrop Grumman TESAR Synthetic Aperture Radar (SAR) with 1-foot resolution and all-weather reconnaissance capability. In 2001 Predator became the first armed UAV with the addition of the laser guided AGM-114 Hellfire air-to-surface anti-armor missile. The U.S. Central Intelligence Agency (CIA) first used armed Predators in Operation Enduring Freedom. As well as the Predator, the U.S. Marine Corps (USMC) RQ-2A Pioneer (1980) and U.S. Army RQ-5A Hunter (1995) also proved themselves in combat. See Table 2 in Appendix A for technical details of the 21st century first generation UAVs.

The first generation Lockheed Martin DarkStar and the Global Hawk were designed with completely programmable control systems using Global Positioning System (GPS) for autonomous operations from takeoff to landing. They were also designed to be used with a common ground control station.

B. 21st Century Second Generation UAVs[2]

The second generation of 21st century UAVs benefited from the first generation's technology advances and significantly increased payload, targeting, reconnaissance and other mission capabilities. The Fire Scout UAV was a rotorcraft with more complex flight controls than fixed wing aircraft. The Fire Scout and the X-47B were designed for autonomous shipboard operations, perhaps the biggest software architecture challenge.

In April 2003 the U.S. Air Force and U.S. Navy started the Joint Unmanned Air Combat Systems (J-UCAS) program for UAVs that would laser designate targets, conduct Suppression of Enemy Air Defense (SEAD) Missions on their own, and attack heavily fortified, high-value targets. "Back in 1997, Air Force Colonel Mike Francis, the director of architecture and integration at the Defense Airborne Reconnaissance Office told David Fulghum of *Aviation Week* that his agency was taking an enthusiastic interest, not just in arming drones, but in developing aircraft that could fly a full mission profile of an armed reconnaissance or strike aircraft."[2] UCAVs were not expendable but "attritable" – they could afford to lose one but not a manned crew aircraft.

As can be seen in Table 3 Part I in Appendix A Boeing's X-45A technology demonstration article had a maximum gross takeoff weight of 12,190 lbs. and on 24 March 2004 successfully dropped an inert 250-pound bomb while flying 442 mph at 35,000 ft.[2] The follow on X-45C which was designed for fielding, had a maximum gross takeoff weight of 36,500 lbs. and carried two GBU-31 Joint Direct Attack Munitions (JDAM) guided bombs.

The U.S. Navy's Unmanned Combat Air Vehicle – Navy (UCAV-N) prototype, the Northrop Grumman X-47A Pegasus had the same mission as the USAF UCAV. It was a stealthy UCAV for surveillance, strike and SEAD but the missions had to be performed from an aircraft carrier. The X-47A Pegasus technology demonstrator had a maximum gross takeoff weight of 5,500 lbs. The X-47B Pegasus is 38.2 ft. long with a wingspan of 62.1ft., maximum gross takeoff weight of 44,567 lbs., payload capacity of 4,500 lbs., and carries two GBU-31 JDAM guided bombs. “The X-47B was designed for longer endurance than the X-47A, high survivability, and low speed aerodynamic flying qualities for autonomous launch and recovery during aircraft carrier operations.”[2]

In April 2003 UCAV program became the Joint-Unmanned Combat Air Systems (J-UCAS) Program encompassing both the USAF X-45C and USN X-47B. In 2006 the joint program became a U.S. Navy UCAS-N and the X-45 was terminated. “All UAVs operating above the designated coordinating altitude must have common, interoperable systems to facilitate….safe and seamless operations,” the USAF asserted in an official 2007 fact sheet.[2] These aircraft included USAF MQ-1 Predator, the RQ-4 Global Hawk, MQ-9 Reaper and USNs Broad Area Maritime Surveillance (BAMS) system. [2]

The USMC MQ-8B Northrop Grumman Fire Scout UAV rotorcraft was designed in 2002 for a multi-mission role with autonomous shipboard landing and takeoff capability, electro-optical/infrared systems, laser designator, and growth payloads for mine countermeasures. The UAV missions include battle management, chemical and biological weapons reconnaissance, signals intelligence, electronic warfare, combat search and rescue, communications and data relay, information warfare, ship missile defense, and anti-submarine warfare. The MQ-9B was 22.87 ft. long when folded with 27 ft. 6 in. rotor diameter and had a 3,150 lbs. gross weight. It was the first helicopter to land on a moving ship without a pilot and its first operational deployment was in 2009. [2]

The USMC Insitu/Boeing Scan Eagle UAV was a long endurance tactical recon fixed wing drone. Its first flight was in 2002, and its 24-hour endurance was much greater than other UAVs of similar size. It had a maximum takeoff gross weight of 44 lbs. and capabilities included autonomous flight (pre-programmed course) and shipboard operations.[2]

The U. S. Navy's MQ-4C Broad Area Maritime Surveillance (BAMS) Unmanned Aircraft System (UAS) is a multi-mission system to support strike, signals intelligence, and communications relay. The MQ-4C BAMS UAS missions include maritime surveillance, collection of enemy order of battle information, battle damage assessment, port surveillance, communication relay, and support of the following missions: maritime interdiction, surface warfare, battle space management, and targeting for maritime and littoral strike missions. With a contract award in 2008, the MQ-4C BAMS UAS uses a maritime derivative of the RQ-4 Northrop Grumman Global Hawk equipped with a 360 degree Multi-Function Active Sensor (MFAS) active electronically scanned array along with Navy-specific ground stations.[2]

IV. Architecture Evolution

In 2003 Samad and Balas[3] edited a volume of research work in support of the Defense Advanced Research Project Agency (DARPA)-sponsored Software Enabled Control (SEC) program. Up to this time, military UAVs had only preprogrammed or remotely controlled operation. Under the SEC program, the goal was for UAVs to “automatically execute high performance maneuvers, dynamically adapt its route, detect and evade threats, identify and compensate for faults, undertake takeoff and landings, and tolerate extreme environmental variations…”[3] The goal of the SEC program is to integrate advanced control with state-of-art computing by an Open Control Platform (OCP) which uses Commercial Off the Shelf (COTS) components and non-proprietary interfaces. UAV control should have an online optimization engine (problem solving algorithm). Previously this algorithm was computationally prohibitive due to the real-time fast dynamics of an aircraft. Samad and Balas indicate “computing resources are now available to perform complex state and model optimization.”[3] They also observe that a strictly defined hierarchical architecture will enable separate areas such as mission re-planning, route optimization, threat avoidance, etc. to be effectively integrated but is costly to performance. The hierarchical structure, however, limits speed of reaction and therefore, they suggest looking at alternative architectures such as those found in biology. Their bottom line is that only by combined research in control engineering and computer science will complex UAV operation solutions be found.

A. Open Control Platform

Paunicka et al.[11] as part of the SEC Program provide an Open Control Platform (OCP) with many real-time systems application services that can be simulated for the controls design engineer. It has a plug and play design such that software components can be developed by different organizations at different times. Its development was led by the Boeing Company and is based on a Boeing Bold Stroke software, as well as middleware developed at Washington University.

The OCP is an object-oriented software infrastructure that "provides a path for quick transition of controls design to desktop and embedded targets. It allows a controls designer to focus on controls design instead of software design by handling the issues of integration, communication, distribution, portability, execution, scheduling, system configuration, and resource management."[11] The core of OCP uses a Common Object Request Broker Architecture based on (COBRA) middle platform and open standards targeted for real-time embedded platforms in the mission avionics domain.

The OCP consists of: 1) Middleware framework based on Real Time (RT) CORBA (Copyright © 2002, Object Management Group, Inc.) which provides a communication network that connects objects to components in a distributed client/server relationship; 2) simulation environment; 3) tool integration support; and 4) controls Application Programmer Interface (API). The OCP middleware is written in C++ and provides a publish/subscribe environment on the main computer or other distributed computers without changing the source code. CORBA also provides a naming service that allows component to retrieve and store references to portable components. This service and others can be seen in Figure 2.[11] Boeing uses a very similar CORBA middleware on their fighter jets F-15, F/A-18, AV-8B, T-45, and DARPA/USAF Unmanned Combat Air Vehicle (UCAV).

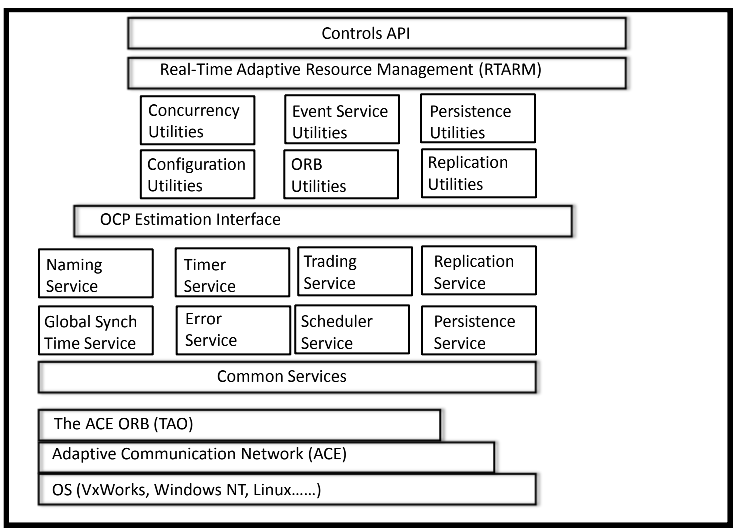

Figure 2. OCP Layered Architecture (2003)[11]

B. WITAS Distributed UAV Architecture

Doherty et al. in 2004 presented "A Distributed Architecture for Autonomous Unmanned Aerial Vehicle Experimentation"[4] which supports development of intelligent capabilities. This distributed architecture uses COBRA for infrastructure for a plug and play hardware/software environment and is based on a reactive concentric software control philosophy. This distributed architecture is used for their Wallenberg Information Technology and Autonomous Systems Laboratory (WITAS) Unmanned Aerial Vehicle Project. WITAS is a mini-UAV helicopter for traffic monitoring and surveillance, emergency services assistance, photogrammetric services and surveying. The test model is a Yamaha RMAX with length of 11.81 ft. and maximum gross takeoff weight of 209 lbs. Their biggest design challenge was the control system which uses several different control modes that are enabled by the architecture to be called dynamically. The design uses a software architecture that has a deliberative, reactive and control components that are not a layered architecture but rather a "reactive concentric" architecture. The reactive concentric architecture is a highly distributed, loosely coupled and concurrent architecture with a number of interacting controls and service processes going on concurrently. CORBA is the middleware that connects the objects and components through a communication service that establishes the client/server relationship. Figure 3 shows some high level software components of the WITAS architecture.

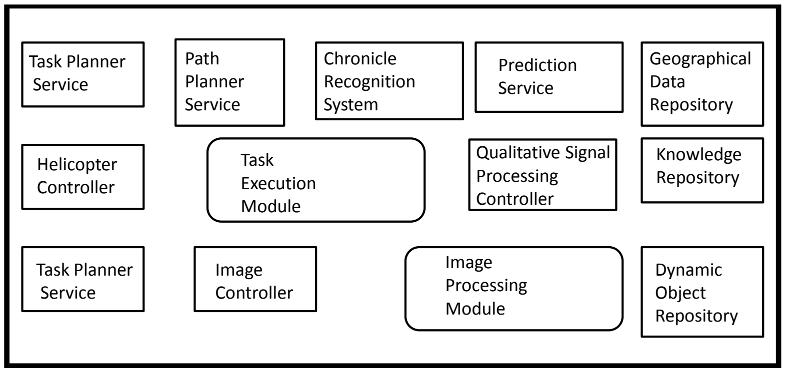

Figure 3. Distributed UAV WITAS Architecture software components (2004)[4]

C. ARL/PSU Intelligent Controller

Sinsley, Long, Niessner, and Horn in 2008[5] discuss a UAV software behavior-based architecture that is both intelligent and autonomous. Long et al.[9] previously provided a comprehensive historical review of several software architectures (1986-2002) that could be used in UAV applications (all lack ability to learn). The 2008 UAV Intelligent Systems Software study used the Applied Research Laboratory at Pennsylvania State University (ARL/PSU) Intelligent Controller (IC) architecture. The IC architecture is a behavior-based (vs. model-based) architecture designed with hierarchical control layers which increases in capability complexity from the bottom-up. It was modified to include a requirement for collaborative capabilities. Figure 4 shows the IC architecture consists of perception and response modules. The perception module creates a representation of the external real world by receiving input data from sensors. The response module creates a plan to perform a specific task using real world awareness created by the perception module. The three level hierarchy has a top level Mission Manager which responds to middle level behaviors (e. g., attack plan implementation) requesting control. Lower level Actions generate output commands (e. g., to autopilot, sensors, send messages). Multiple Behaviors can be implemented if they do not cross paths. According to Long et al.,[9] some key features of the IC architecture include the ability to react to unplanned situations, automatic on-the-fly dynamic planning, situational awareness, common architecture for multi-vehicle collaboration, and the flexibility to include new capabilities and optional human interaction at any level. The test model is a fixed-wing SIG Kadet Senior (gross weight 14 lbs.) with stable flight characteristics and slow flying speed.

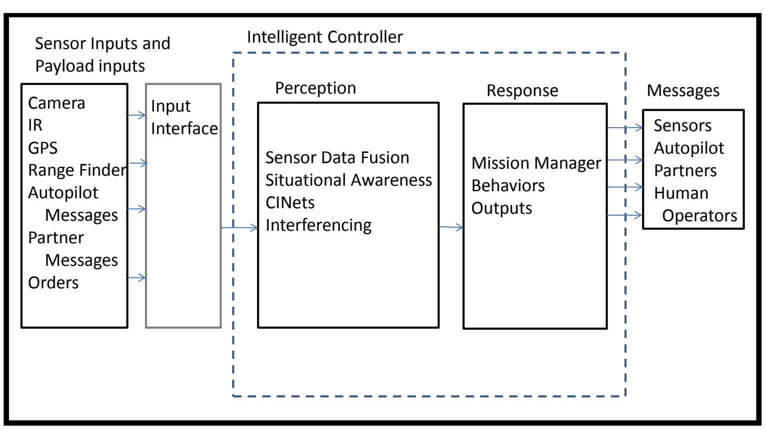

Figure 4. ARL/PSU Intelligent Controller High Level Architecture (2008)[5]

For an in-depth discussion of the IC architecture see Stover and Kumar "A Behavior based Architecture for the Design of Intelligent Controllers for Autonomous Systems"[10].

D. SheLion UAV System

Cai, G., Chen, B., and Lee, T., in *Unmanned Rotorcraft Systems*[6] describe a behavior-type architecture they used to design their miniature SheLion UAV that could be extrapolated for use on larger UAVs. Their software systems complete tasks such as hardware driving, input/out, control law implementation, device operation management, multitask scheduling, and event scheduling. They report use of a new type of software system/behavior architecture that provides flexibility and extensibility for new modules and control functionalities. They indicate the architecture can be applied universally to unmanned aerial vehicles, and consists of the onboard software system and the ground control station software system.

The onboard software system uses a Real-Time Operating System (RTOS), which includes a flight control and a vision processing module based on the avionic system hardware configuration shown in Figure 5.

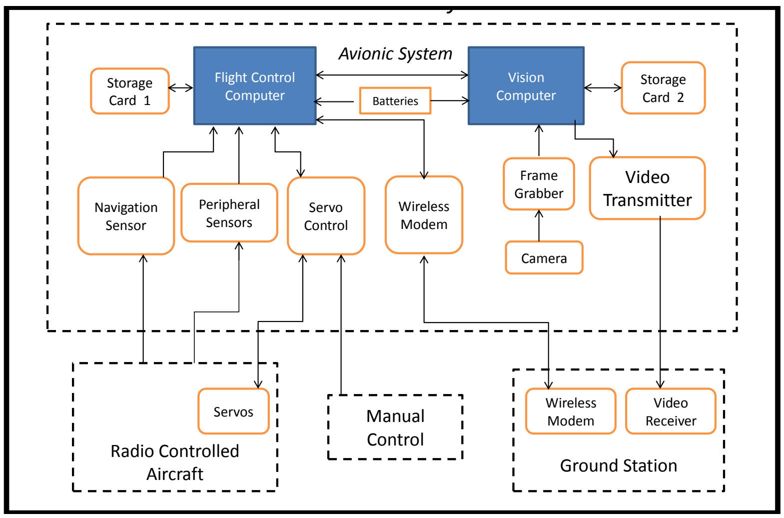

Figure 5. Hardware Configuration of SheLion UAV System (2011)[6]

For the flight control module a multiple thread framework is used for operating navigation sensors and servo actuators, logging in-flight data, communicating with the ground station and implementing automatic control algorithms. For automatic control, a behavior-based architecture[8] is employed. The framework of the SheLion flight control system is shown in Figure 6.

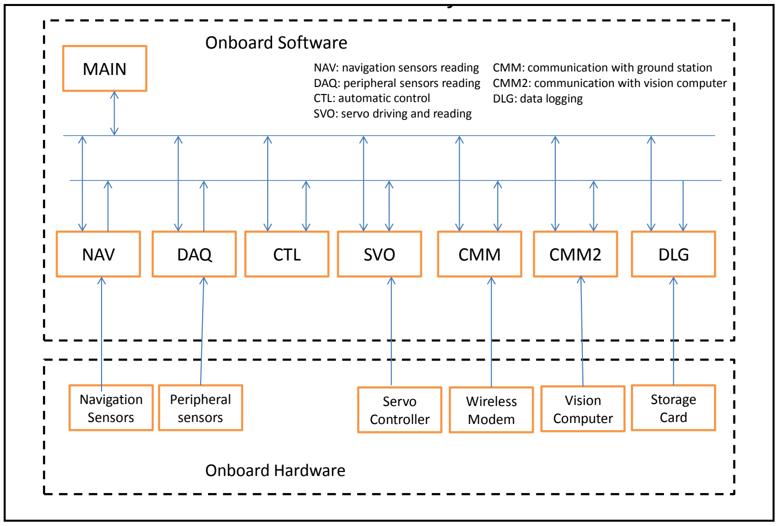

Figure 6. Framework of SheLion Flight Control Software System (2011)[6]

A similar framework is used for the onboard vision computer for real-time image processing. The flight control software framework of Figure 6 is organized into blocks for each device or task. The NAV block interacts with the GPS-aided Attitude Heading Reference System (AHRS), brings in measured in-flight data and estimates unmeasured flight states (necessary for automatic control). The CTL block implements automatic flight control laws. It obtains flight status from globally shared data generated by the NAV Block, executes control algorithms based on flight status, and generates control signals to drive servo actuators. Task management uses a multi-thread architecture in which every thread is an individual task. Task scheduling is done by a MAIN thread that uses a high-precision timer (nanosecond accuracy) to emit a pulse signal that activates the MAIN thread in a predefined frequency. A time range/slot is allocated to each of the threads depending on the complexity of their functions.[6]

Cai et al.[6] use a behavior-based flight scheduling block to distinguish various flight patterns. Flight plans can be stored on the UAV helicopter flight scheduling block or generated from the ground station. Any operation of the UAV helicopter is recognized as specific behavior with specific parameters (e.g., control signals and execution time limitations). A hierarchical control system block (CTL) is used to recognize behavior and implement corresponding automatic control algorithm that drives the servo actuators.

The SheLion ground control station is a wireless terminal for users to monitor and command the UAV helicopter. In flight tests, data are transferred from the onboard system to the ground station and displayed. This framework for the SheLion ground control station is shown in the Figure 7.

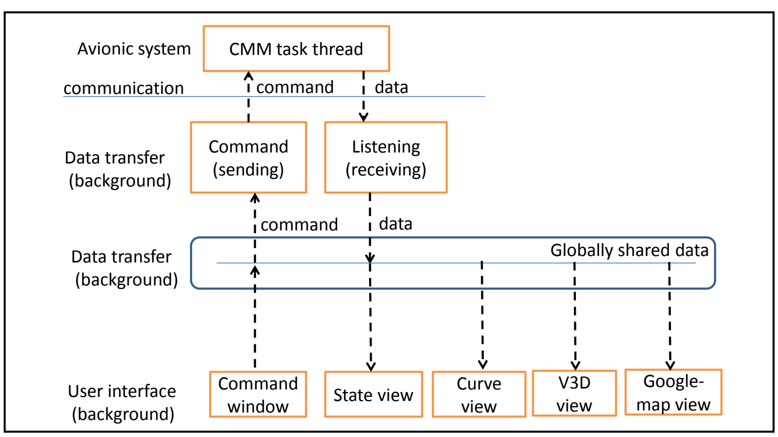

Figure 7. Framework of SheLion Ground Control Station Software System (2011)[7]

V. Future UAVs

According to a Request for Information (RFI) released March 2010, the USN solicited additional information for an Unmanned Carrier Launched Surveillance and Strike (UCLASS) UAV, the follow up to the Northrop Grumman X-47B Pegasus UCAS-D. The Deputy Chief of Naval Operations (DCNO) for Information Dominance (N2/N6) has identified a need for an aircraft carrier based aircraft system providing persistent intelligence, surveillance and reconnaissance (ISR) and precision strike capabilities. The Navy is interested in a carrier-based operational unmanned air system capable of integrating with manned platforms as part of the carrier Air Wing.[12]

VI. Summary

The early 1940 RC aircraft UAVs used for aerial target aircraft and later as observation platforms by the USAAF did not have software architectures. The AQM-34L Lightning Bug (1964-1975), precursor to the 21st century UAV, had advanced technology capabilities of real-time television imagery, electronic radar jammers, and AN/ALE-38 chaff dispensers.

UAVs around the turn of the century benefited by increases in satellite capabilities and technology advances in computer processing power, algorithm development, use of real-time systems, electromechanical flight control systems, vision/radar systems, navigation systems, and weapons system integration computers. All of these first generation capabilities affected software architecture development. The General Atomics' Predators and the Northrop Grumman RQ-4 Global Hawk were the main UAVs in this category. The Global Hawk was designed with completely programmable control systems using Global Positioning System (GPS) for autonomous operations from takeoff to landing. They were also designed to be used with a common ground control station.

The second generation of 21st century UAVs benefited from the first generation's technology advances and significantly increased payload, targeting, reconnaissance and other mission capabilities. The Fire Scout UAV was a rotorcraft with more complex flight controls than fixed wing aircraft. The Fire Scout and the X-47B were designed for autonomous shipboard operations, perhaps the biggest software architecture challenge. The U.S. Navy's Unmanned Combat Air Vehicle (UCAV) Northrop Grumman's X-47B Pegasus was designed for "long endurance, high survivability, and low speed aerodynamic flying qualities for autonomous launch and recovery during aircraft carrier operations."[2] The U.S. Navy's MQ-4C Broad Area Maritime Surveillance (BAMS) Unmanned Aircraft System (UAS) is a multi-mission system to support strike, signals intelligence, and communications relay. It uses a maritime derivative of the RQ-4 Northrop Grumman Global Hawk equipped with a 360 degree Multi-Function Active Sensor (MFAS) active electronically scanned array along with Navy-specific ground stations.

UAV architectures investigated in this paper use a combination of those shown by Garlan and Shaw[1] in Figure 1 – Control Loop, Layered Hierarchical, Implicit Invocation and Blackboard. Behavior-based architecture (vs. model based) with hierarchical organization is the most popular if not optimum structure for UAV software architecture. Use of real-time systems and autonomous controllers is state of the art. Samad and Balas indicated in 2003 that "computing resources are now available to perform complex state and model optimization (for the real-time fast dynamics of an aircraft)."[3] Doherty et al. use a CORBA/client server/distributed "architecture with number of interacting controls and service processes going on concurrently." Sinsley, Long et al.[5] have developed the closest to an artificial intelligence software flight controller with the ARL/PSU Intelligent Controller (IC) that uses a behavior-based architecture. A form of Paunicka et al.'s[11] CORBA/layered architecture for UAVs is already being used on F/A-18 aircraft for carrier-based operations and should be adaptable for future UCLASS autonomous shipboard take-off and landings. This is the latest in the evolutionary chain from the radio (non-software) controlled technology of the 1940's.

U.S. DOD plans to increase UAV inventory totals by 45 percent[13] in the next decade and has an Unmanned Control Systems, Control Segment Working Group to create a common architecture and open standards for UAV ground stations. [14] The U.S. Navy has issued a Request for Information (RFI) for a new sixth generation fighter to replace the shipboard based Boeing F/A-18E/F Super Hornet and EA-18G Growler in the 2030s that could possibly be a UAV.[15]

References

[1] Garlan, D. & Shaw, M. *Software Architecture: Perspectives on an Emerging Discipline*, Prentice Hall, 1996.

[2] Yenne, W., *Birds of Prey, Predators, Reapers and America's Newest UAVs in Combat,* Yenne, W., Specialty Press, 2010, Pgs. 51, 60, 84, 153.

[3] Samad, T., and Balas, G. editors, *Software Enabled Control, Information Technology for Dynamical Systems*, IEEE Press, Wiley-Interscience, 2003, Pgs. 395, 398.

[4] Doherty, P., Haslum P., Heintz, F., Merz, T., Nyblom, P., Persson, T., and Wingman, B**.**,"A Distributed Architecture for Autonomous Unmanned Aerial Vehicle Experimentation," In proceedings of the 7th International Symposium on Distributed Autonomous Systems, 2004.

[5] Sinsley, G., Long, L., Niessner, A., and Horn, J., "Intelligent Systems Software for Unmanned Air Vehicles," presented at 46th AIAA Aerospace Sciences Meeting, Reno, NV Jan., 2008, AIAA paper No. 2008-0871

[6] Cai, G., Chen, B., and Lee, T., *Unmanned Rotorcraft Systems*, Springer, 2011.

[7] Defense Acquisition University, ACQ 101 Fundamentals of Systems Acquisition Management, 2011, Lesson 21: Software Acquisition: Fundamentals.

[8] Dong, M., and Sun, Z. "A Behavior-based Architecture for Unmanned Aerial Vehicles," Proceedings of the 2004 IEEE International Symposium on Intelligent Control, Taipei, Taiwan, September 2-4, 2004.

[9] Long, L., Hanford, S., Janrathitikarn, O., Sinsley, and Miller, J., "A Review of Intelligent Systems Software for Autonomous Vehicles," Proceedings of the 2007 IEEE Symposium on Computational Intelligence in Security and Defense Applications (CISDA 2007).

[10] Stover, J. and Kumar, R., "A Behavior based Architecture for the Design of Intelligent Controllers for Autonomous Systems," Cambridge, MA, September 15-17, 1999.

[11] Paunicka, J. L., Mendel, B. R., and Corman, D., "Open Control Platform Supporting Advances in UAV Control Technology," *Software Enabled Control, Information Technology for Dynamical Systems*, Samad, T., and Balas, G. editors, IEEE Press, Wiley-Interscience, 2003, Pg. 40.

[12] US Department of the Navy, Naval Air Systems Command, "A-RFI Request for Information for Unmanned Carrier Launched Airborne and Strike (UCLASS) Systems Key Capabilities", Solicitation Number: N0019-UCLASS-RFI-A, 20 Mar 2010, URL: https://www.fbo.gov/index?s=opportunity&mode=form&id=3c621aa3f10b785132ca7c2abdabf75f&tab=core&tabmode=list& [cited 21 May 2012]

[13] US DOD "Annual Aviation and Inventory Funding, Fiscal Years (FY) 2013-2042", March 2012 Pg 6, , URL: http://www.defenseinnovationmarketplace.mil/resources/Annual%20Aviation%20Inventory%20and%20Funding%20Plan%202013-2042.pdf [cited 21 May 2012]

[14] US Department of the Army, "10--Unmanned Aircraft System Control Segment Architecture Industry Days," Solicitation Number: W58RGZ-INDUSTRY-DAYS, 30 Apr 2009, URL:https://www.fbo.gov/?s=opportunity&mode=form&id=4a157aba6a8abab94e3eabcbb8d9b998&tab=core&_cview=0 [cited 21 May 2012]

[15] Malumdar, D. "US Navy issues F/A-XX RFI", *Flightglobal*, 18 Apr 2012.

Appendix A

Table 1. 20th Century UAVs[2]

Title	Prime Contractor/ Time Period	Operation	Propulsion	Length/ Width/ Gross Weight	Endur-ance	Speed/ Range/ Ceiling	Mission	Guidance	Software Capabilities
OQ-1 (1941)	Radioplane /(1952 Northrop Grumman)/ World War II	US Army Air Forces/later US Navy	Miniature piston/larges t 22-hp	8 ft 8 in/ 12 ft 3 in/	longest 1 hr.	85 mph	Aerial target drone/ later observatioon	Radio-controlled	
Q-2/Ryan Firebee (1948)	Ryan Aeronautical Company	US Navy Trainer/ USAF	Hybrid piston engine with auxiliary jet engine	17 ft 3 in/ 11 ft 2 in		.9 mach/ 400 mi/ > 50,ooo ft	Recoverable Target Drone/ first to be used for observation, air		
BQM-34A /Firebee II/Lightnin g Bug (1962)	Ryan Aeronautical Company/	USAF/CIA/Navy (Model 147SK launched with rocket booster from aircraft carrier	Continental J69-T-406 turbojet	29 ft 2 in / wingspan 8 ft 11 in		Mach 1.1/900 mi/60K	spy plane	Electro-optically guided	
AQM-34L Lightning Bugs RPV (1964-1975)	Teledyne Ryan/ Southeast Asia/ recon/combat roles	USAF flew 121 missions after June 1972 involved real-time television imagery					Precursor 21st Century UAV		photo-reconnassai nance, real-time television
MQM-74C/ Chukar II (1974)	Radioplane/ Northrop Ventura	US Navy Aerial Target/ Reconnaisance/ Launched from ship using rocket assist, Chukar III optional onboard video system (Operation Desert Storm 1991 Firebees and Chukars used as decoys)	Williams 1400-WR-400 turbojet engine	12ft 8in/ wingspan 5ft 9in/ 500lbs		575mph /400m/4 0K ft ceiling			
US Army RQ-5A Hunter (1995)	Israeli Aircraft Industries (IAI)	Assembled in US by TRW which later became Northrop Grumman)		22 ft 10 in/ 29 ft 2 in	12 hrs	<15000 ft			
USMC RQ-2A Pioneer (1980)	Evolved from original Hunter	Shipboard based, operation allied force against Yugoslavia		16 ft 11 in/ 14 ft wingspan	5.5 hours	92 mph/ 15,00 ft/ 450 mi			

Appendix A

Table 2. 21st Century First Generation UAVs[2]

Title	Prime Contractor/Time Period	Operation	Propulsion	Length/ Wing Span/ Gross Weight	Payload Weight/ Materials	Endurance/ Armanent	Speed/ Range/ Ceiling	Mission	Guidance	Software Capabilities
RQ-3 DarkStar (1994)	Lockheed Martin	Large, futuristic stealth TIER III, First flight 29 Mar 1996 (autonomous take-off), terminated 29 Jan 1999	Williams FJ-44-1 turbofan engine	15ft Length/Wing Span 69ft/ Gross Weight 8,600 lbs	non-metal composites, no vertical tail surfaces		345 mph, endurance 12.7 hrs or 8 hrs above 45,000 ft	Interface common mission ground control station	Completely programm-able control systems	Autonomous operations from takeoff to landing
RQ-4 Global Hawk (1997)	Teleydyne Ryan (1995)/Northop Grumman (1999)	Long endurance high altitude reconnasaince Tier II, first flight 28 Feb 1997, Operation Enduring Freedom 2001 (Afgahanistan)	Rolls-Royce-Allison AE3007H turbofan; 7,600 lb thrust	Same class size U-2, Original 44ft long/ wingspan 116ft/Gross Weight 25,600lbs	Aluminum fuselage, composite wing	42hrs maximum (on ststion 24 hrs)	Fully fueled 13,000 mi, 65,000ft/ No armament specified	Interface common mission ground control station	Completely programm-able control systems	Autonomous operations from takeoff to landing; Electro-Optical/Infrared (EO/IR) and Synthetic Aperature Radar (SAR) (3-ft resolution)
RQ/MQ-1 Predator (USAF) (1994)	General Atomics Aeronautical Systems (1994)	Tier II Medium altitude reconnasaince, RQ-1 changed MQ-1 2002 with armed reconnaissance role, first flight 1994, Operational over Balkans 1995	4-cylinder, 4 stroke 115-hp Rotax engine	Inverted V-tails, slender fuselage, Length 27 ft/48.7 ft wingspan / gross TO weight 2,250 lbs	NGC TESAR synthetic aperature radar (SAR) (1-ft resolution), laser designator and rangefinder, electronic support and countermeasures, moving target indicator, Raytheon Multi-Spectral Targeting System provides real-time imagery. Payload 500 lbs.	40 hrs/(2001) added laser guided AGM-114 Hellfire, 100lbs, air-to-surface anti-armor missile	Cruise 84 mph; top 135 mph	Persistent surveillance, strike mission (addition of laser designator /thermal image Raytheon AN/AAS-44 (V) sensor turret)	Forward looking camera, lot losses from hitting ground landing/ lack situational awareness (operator error)	

Appendix A

Table 3. 21st Century Second Generation UAVs[2] – Part I

Title	Prime Contractor/Time Period	Operation	Propulsion	Size/Gross Weight	Payload Weight/ Materials	Endurance	Speed/ Range/ Ceiling	Mission	Guidance	Software/ mission Capabilities
X-45A Peace-keeper Techno-logy Demon-strator (UCAV) (2002)	Mcdonnell Douglas/Boeing (1998), first flight Nov 2002/ DARPA USAF program	SEAD mission, autonomous operations,	Honeywell F124-GA-100 turbofan engine	26 ft Long/ Wingspan 34 ft/No vertical tail surfaces/ Max Gross T.O.Weight 12, 190 lbs	1500 lb		Mach 0.75/570 mi/35,000 ft	Low-observable stealth technology, SEAD mission, track high value targets		Targeting software/ real-time on-board and off-board sensors for quick detection, identification, and location of fixed, relocatable, and mobile targets.
X-45C Peacekeeper (UCAV) (DARPA)	McDonnell Douglas/Boeing terminated 2006		general Electric F404-GE-102D turbofan	39 ft Long/ 49 ft Wing span/ Max Gross T.O.Weight 36,500 lbs	4,500 lbs/ Two GBU-31 Joint Direct Attack Munition Guided Bomb/two weapons bays		Mach 0.85/1,500 mi/40,000 ft	low-observable stealth technology, SEAD, track high value targets		Synthetic Aperature Radar, electronic support measures (ESM), MILSTAR satellite interface, and aerial refueling, guided air-to surface
X-47A Pegasus (UCAV-N) (USN) Techno-logy Demon-strator (2001)	Northrop Grumman (2001), first flight 2003 at China Lake, CA	Same mission as USAF UCAV - stealthy UCAV for surviellance, strike, and Suppression of Enemy Air defenses (SEAD) - but from aircraft carrier.	Pratt 7 Whitney JT15D-5C turbofan engine, 3,200 lbc thrust	Kite shaped 27 ft 11 in long, 27 ft 10 in wingspan, no vertical surfaces 6 ft tall, 3,835 lb dry with total fuel capacity 1,580 lbs,	non-metal composites (Scaled Composites, Mojave, CA)			Surveil-lance, strike, SEAD, carrier operations, stealth		
X-47B Pegasus (UCAV-N) (USN) (2003)	Northrop Grumman (2003), merger X-45 into X-47 J-UCAS program, first flight 2003 at China Lake, CA? US Navy's UCAV-N program			Kite shape blended into flying wing						

Appendix A

Table 3. 21st Century Second Generation UAVs[2] - Part II

Title	Prime Contractor/Time Period	Operation	Propulsion	Size/Gross Weight	Payload Weight/ Materials	Endurance	Speed/ Range/ Ceiling	Mission	Guidance	Software/ mission Capabilities
MQ-9 Reaper (USAF) (2001)	General Atomics Aeronautical Systems/larger Predator/carbon fiber composites	Tier II medium altitude long endurance	Honeywell TPE331-10GD turboprop	66 ft wingspan, 36 ft length, 12.5 ft hieght, 10,000 lbs max gross T.O. weight	AGM-114 hellfire missile		230 mph, 50,00 ft ceiling, 3,682 mi range, 40 hrs endurance			Armament: AGM-114 Hellfire Missile, GBU-12 Paveway II and GBU-38 Joint Direct Attack Munitions
MQ-8B Fire Scout (USMC) (2002)	Teledyne Ryan/Northrop Grumman (2002) first armed rotocraft UAV, first flight May 2002	Replace Pioneer, continuous surveillance capability exceeding 6 hr, operational radius 100 mi, real-time battle damage assessment, first helicopter land on moving ship with man controller, first operational deployment 2009	Rolls Royce 250-C20 turboshaft	22.87 ft long folded/27 ft 6 in Rotor dia/3,150 lbs Gross Weight	600 lbs/ 2.75-inch Advanced Precision Kill Weapon System (APKWS) rockets		125 mph/8hrs/ 20,000 ft	USMC Reconnaissance, shipboard operations, strike mission		Autonomous shipboard landing and take off, electro-optical/infrared systems, laser designator, growth payloads for mine countermeasures, battle management, chemical and biological weapons reconnaissance, signals intelligence, electronic warfare, combat search and rescue, communications and data relay, etc
Scan Eagle (2004)	Insitu group of Bingen, Washington	First flight 2002, USMC long endurance tactical recon drone (24 hrs much greater than other similar size)	Sonex Research (1.9 hp)	4.5 ft long/Wingspan 10.2 ft, (same RQ-7)/44 lbs max takeoff weight		24 hrs plus	90 mph /19.500 ft Ceiling	Intelligence, surveillance, recon support		Autonomous flight (pre-programmed course)/Ship-board operations
Global Hawk (USN) (RQ-4 maritime derivative) (2008)	Northrop Grumman Broad Area Maritime Surveillance (BAMS) program (2007)	Maritime surveillance, battle damage assessment, communication relay		44.4 ft length/ 130.9 ft Wingspan/ 32,250 lb max Gross TO weight			357 mph Speed/14, 155 mi Range /65,000 ft Ceiling			

Bibliography

Albus, J., "4D/RCS, A Reference Model Architecture for Intelligent Unmanned Ground Vehicles", In proceedings of the SPIE 16th Annual International Symposium on Aerospace/Defense Sensing, Simulation and Controls, Orlando, FL, April 1-5, 2002.

Bhattacharya, R., and Balas, J., "Implementation of Online Control Customization Within the Open Control Platform," *Software Enabled Control, Information Technology for Dynamical Systems*, IEEE Press, Wiley-Interscience, 2003.

Cai, G., Chen, B., and Lee, T. Unmanned Rotorcraft Systems, Spronger-Verlag, 2011.

Doherty, P., "Advanced Research with Autonomous Unmanned Aerial Vehicles," Copyright 2004 American Association for Artificial Intelligence.

Doherty, P., Haslum P., Heintz, F., Merz, T., Nyblom, P., Persson, T., and Wingman, B**.**, "A Distributed Architecture for Autonomous Unmanned Aerial Vehicle Experimentation," In proceedings of the 7th International Symposium on Distributed Autonomous Systems, 2004.

Doherty, P., Granlund, G., Kuchcinski, K., Sandewall, E., Nordberg, K., Skarman, E., and Wiklund, J., "The WITAS Unmanned Aerial Vehicle Project," In W. Horn (ed.): ECAI 2000. Proceedings of the 14th European Conference on Artificial Intelligence, IOS Press, Amsterdam, 2000.

Dong, M., and Sun, Z. "A Behavior-based Architecture for Unmanned Aerial Vehicles," Proceedings of the 2004 IEEE International Symposium on Intelligent Control, Taipei, Taiwan, September 2-4, 2004.

Garlan, D. and Shaw, M. *Software Architecture: Perspectives on an Emerging Discipline*, Prentice Hall, 1996.

Kieras, D., and Meyer, D., "An overview of the Epic Architecture for Cognition and Performance With Application to Human-Computer Interaction," Human-Computer Interaction, 1997, Volume 12, pp. 391-438, Copyright 1997, Lawrence Erlbaum Associates, Inc.

Long, L., Hanford, S., Janrathitikarn, O., Sinsley, and Miller, J., "A Review of Intelligent Systems Software for Autonomous Vehicles," Proceedings of the 2007 IEEE Symposium on Computational Intelligence in Security and Defense Applications (CISDA 2007).

Martin, F. "Integrating Hardware experiences into a Computer Architecture Core Course," Consortium for Computing Colleges, 2006.

Nesnas, I., Simmons, R., Gaines, D., Kunz, C., Diaz-Calderon, A., Estlin, T., Madison, R., Guineau, J. McHenry, M., Shu, I., and Apfelbau, D., "CLARAty: Challenges and Steps Toward Reusable Robotic Software," International Journal of Advanced Robotic Systems, Vol. 3, No. 1 (2006), ISSN 1729-8806, pp. 023-030.

Oberoi, S. "Sensor fusion brings situational awareness to health devices," Embedded Systems Design Volume 24, Number 5, June 2011.

Paunicka, J. L., Mendel, B. R., and Corman, D., "Open Control Platform Supporting Advances in UAV Control Technology," *Software Enabled Control, Information Technology for Dynamical Systems*, Samad, T., and Balas, G. editors, IEEE Press, Wiley-Interscience, 2003.

Samad, T., and Balas, G. editors, *Software Enabled Control, Information Technology for Dynamical Systems*, IEEE Press, Wiley-Interscience, 2003.

Samad, T., and Balas, G., "The Outlook for Software enabled Control," *Software Enabled Control, Information Technology for Dynamical Systems*, IEEE Press, Wiley-Interscience, 2003.

Schoeberl, M., “Time-Predictable Computer Architecture,” Hindawi Publishing Corporation, EURASIP Journal on Embedded Systems, Volume 2009, Article ID 758480, 17 pages, doi:10.1155/2009/758480.

Shima, T. and Rasmussen, S. *editors UAV Cooperative Decision and Control Challenges and Practical Approaches*, Society for Industrial and Applied Mathematics 2009.

Sinsley, G., Long, L., Niessner, A., and Horn, J., “Intelligent Systems Software for Unmanned Air Vehicles,” presented at 46th AIAA Aerospace Sciences Meeting, Reno, NV Jan., 2008, AIAA paper No. 2008-0871.

Sinsley, G., Long, L., Niessner, A., and Horn, J., “Intelligent Systems Software for Unmanned Vehicles” Presented at 46thAIAA Aerospace Sciences meeting, Reno, NV Jan., 2008, AIAA paper No. 2008-0871.

Vilavanis, K., editor *Unmanned Aerial Vehicles,* “Journal of Intelligent & Robotic Systems”, Volume 61, issues 1-4, 2011, Springer science and business media 2011.

Yehezkel, C., Yurik, W., Pearson, M., and Armstrong, D., “Three Simulator Tools for Teaching Computer Architecture; EasyCPU, Little Man Computer, and RTLSIM”, ACM Journal of educational Resources in Computing, Vol, 1, No. 4, December 2001, Pages 60-80.

Yenne, W., *Birds of Prey, Predators, Reapers and America’s Newest UAVs in Combat*, Specialty Press, 2010.

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