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Unmanned Tactical Autonomous Control and Collaboration (UTACC) unmanned aerial vehicle analysis of alternatives

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MONTEREY, CALIFORNIA

THESIS

UNMANNED TACTICAL AUTONOMOUS CONTROL AND COLLABORATION (UTACC) UNMANNED AERIAL VEHICLE ANALYSIS OF ALTERNATIVES

by

Brian M. Roth
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March 2016

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This research determined that an aircraft satisfying established performance characteristics, capable of vertical takeoff and landing, and with a small size and modular payload capability met the requirements needed to further UTACC development. This thesis developed a list of potential aircraft that satisfy the characteristics evaluated and are suitable for research, development, test and evaluation, or operational applications.

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UNMANNED TACTICAL AUTONOMOUS CONTROL AND COLLABORATION (UTACC) UNMANNED AERIAL VEHICLE ANALYSIS OF ALTERNATIVES

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LIST OF ACRONYMS AND ABBREVIATIONS

AC	Air Carrier
ACAT	Acquisition Category
AGL	Above Ground Level
AoA	Analysis of Alternatives
C2	Command and Control
CC	Cubic Centimeter
CJCS	Chairman, Joint Chiefs of Staff
CONOPS	Concept of Operations
COTS	Commercial Off The Shelf
DAG	Defense Acquisition Guidebook
DAS	Defense Acquisition System
DAU	Defense Acquisition University
DOD	Department of Defense
DODI	Department of Defense Instruction
EO	Electro-Optical
FLIR	Forward Looking Infrared
GPS	Global Positioning System
GSE	Ground Support Equipment
GUSS	Ground Unmanned Support Surrogate
HD	High Definition
HOGE	Hover Out of Ground Effect
HRI	Human Robot Interaction
HSI	Human System Interaction
HyAlta	Hybrid Advanced Lighter Than Air
ICD	Initial Capabilities Document
IER	Information Exchange Requirements
IR	Infrared
ISR	Intelligence, Surveillance, Reconnaissance
JCIDS	Joint Capabilities Integration and Development System
JCS	Joint Chiefs of Staff

JP	Joint Publication
LIDAR	Light Detection and Ranging
LOS	Line of Sight
LTA	Lighter-Than-Air
MCWL	Marine Corps Warfighting Laboratory
MIL-STD	Military Standard
MSA	Material Solution Analysis
MSL	Mean Sea Level
MTOW	Maximum Takeoff Weight
NIST	National Institute of Standards and Technology
NM	Nautical Mile
NPS	Naval Postgraduate School
NSWC	Naval Surface Warfare Command
OAS	Office of Aerospace Studies
OS	Operating System
RADALT	Radar Altimeter
RDT&E	Research, Development, Test and Evaluation
SIGINT	Signals Intelligence
SoS	System of Systems
SOW	Statement of Work
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UMS	Unmanned Systems
URL	Uniform Resource Locator
USGS	United States Geological Survey
USMC	United States Marine Corps
UTACC	Unmanned Tactical Autonomous Control and Collaboration
UxS	Unmanned System
V-STAR	VTOL Swift Tactical Aerial Resource
VTOL	Vertical Takeoff and Landing

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I. INTRODUCTION

This thesis conducted an analysis of potential unmanned aerial vehicles suitable for use by the Marine Corps Warfighting Lab (MCWL) in support of the lab's Unmanned Tactical Control and Collaboration (UTACC) research program. According to Rice, Keim and Chhabra, the purpose of UTACC is "to enhance mission accomplishment while simultaneously reducing the cognitive load on the operator through collaborative autonomy between human and machine components" (2015, p. 4). This purpose was discussed and defined in the concepts of operation (CONOPS) developed by Rice et al. (2015), a major component of which is the employment of unmanned aerial vehicles (UAV) and their collaboration with human operators. Following an extensive analysis of numerous UAVs, the authors produced a comprehensive database to determine the best potential aircraft candidate to help facilitate UTACC program development.

A. RESEARCH CONTEXT

Beginning in 2014, MCWL has been conducting research into developing UTACC, a "multi-agent, multi-domain, collaborative unmanned system (UxS)" (Statement of Work [SOW], 2014, p. 1) Built as a system of systems (SoS), it is intended to be a "decision-centric, semi-autonomous, distributive multi-agent, multi-domain robotic system" capable of minimizing operator interaction (SOW, 2014, p. 1).

In order to further develop the collaborative autonomy and human system integration (HSI) concepts required by UTACC, an appropriate UAV system must be employed. The authors utilized a systematic approach described in the Defense Acquisitions System (DAS) to develop a methodology for evaluating the broad array of UAVs currently in production or development. The authors employed this methodology to identify aircraft characteristics that fit the needs of UTACC research into collaborative autonomy and HSI.

A thorough understanding of the research on and concepts of autonomous systems is critical to this study. The DOD recognizes the importance of unmanned systems and their ability to improve battlefield capabilities (Secretary of Defense for Acquisition, Technology, and Logistics, 2013). Active research within the DOD and Marine Corps is seeking to identify greater "operational uses of autonomy across all warfighting domains" (Kendall, 2014, p. 1). This study includes an examination of autonomy and its application to unmanned systems. With this understanding of the importance of autonomy to future warfare, the authors sought to build a comprehensive database of UAVs capable of supporting UTACC research.

B. THESIS FOCUS AND ORGANIZATION

This thesis had three distinct focus areas. First, a database was created consisting of all production and developmental UAVs currently manufactured by United States based contractors. Second, the authors developed detailed metrics with which to analyze and compare these various UAVs within the framework established in the CONOPS study conducted by Rice et al. (2015). Further, the authors employed a systematic approach to developing a process for evaluation using the principles of DAS, specifically the concept of material solution analysis (MSA) and analysis of alternatives (AoA). Finally, the authors recommend suitable UAVs for the research, development, test and evaluation (RDT&E) and operational phases of the UTACC program.

This thesis is organized into four additional chapters. Chapter II is a literature review highlighting the DAS, UAV development and application, and the CONOPS of the UTACC program. This approach allowed for the systematic evaluation of UAVs within the context of the DAS and UTACC concepts. Chapter III details the research methodology describing the development of characteristics that the authors determined to be critical to the development of the UAV capabilities for UTACC. The fourth chapter, the UAV Analysis of Alternatives, describes the nine potential aircraft that are suitable for UTACC based on the characteristics developed in Chapter III. These aircraft are described in detail and were evaluated based on performance, physical specifications and sensor capabilities. In order to provide increased granularity to the reader, the authors include the developed database and aircraft scoring metrics as a supplemental document to accompany this thesis. Because the development of UAVs is moving at such a rapid pace, the database employed for this study must be considered a living document.

Therefore, the final chapter of this thesis describes what MCWL must do to continue to employ the database to track and evaluate UAVs in the future.

C. CHAPTER CONCLUSION

The UTACC program provides an outstanding opportunity to advance the collaboration between humans and unmanned vehicles for the Marine Corps and beyond. This thesis is intended to provide quantifiable data supporting the identification and potential application of a UAV to facilitate further development of UTACC.

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II. LITERATURE REVIEW

There is a great deal of information available regarding the Department of Defense Acquisition System (DAS). Additionally, vast amounts of research are available pertaining to Unmanned Aerial Vehicle (UAV) systems and their varied applications. A thorough understanding of both of these topics is important when examining potential UAVs capable of supporting the requirements of the Unmanned Tactical Autonomous Control and Collaboration (UTACC) program. This chapter reviews key concepts pertinent to the development of a methodology for evaluating UAVs for the UTACC program.

A. UNMANNED TACTICAL AUTONOMOUS CONTROL AND COLLABORATION

UTACC is an alternative warfighting concept being developed by The United States Marine Corps Warfighting Laboratory (MCWL). This alternative warfare concept intends to harness collaborative autonomous technology to enhance mission effectiveness by reducing cognitive load (Rice et al., 2015). This will allow the vast amount of information traditionally processed by humans to be processed by the UTACC system. It will employ a sophisticated collaborative team comprised of both human and robotic warfighters as a "small tactical unit," defined by Rice et al. as "a Marine Corps infantry fire team, infantry squad, or reconnaissance team" (2015, p. 26). Functionally, it will operate as a system of systems (SoS), with high-level operational control overseeing multiple disparate autonomous systems (Rice et al., 2015). In order to meet this conceptual goal and allow for seamless integration of the human and machine elements, the cognitive load placed on the human element must be minimized (Rice et al., 2015).

As discussed, the composition of a conceptual UTACC unit will include a human element and autonomous air and ground vehicles. These ground vehicles will include an autonomous air carrier (AC) capable of supporting unmanned aerial vehicles with ground transport, refueling and launch and recovery operations (Rice et al., 2015). The UAVs will play a critical role in the UTACC system by acting as communication relay nodes and providing intelligence, surveillance and reconnaissance (ISR) information to all other components. In addition, UAVs must be capable of carrying any number of sensors to support this requirement (Rice et al., 2015). Finally, the concept of collaboration between human and machine is critical to the successful implementation of the UTACC concept (Rice et al., 2015).

B. AUTONOMY

As envisioned, the UTACC system will function in a collaborative manner with both human and machine components. This functionality will employ unmanned systems (UMS) in a semi-autonomous application; defined by the National Institute of Standards and Technology (NIST) as the mode of operation in which the human and the unmanned system conduct missions requiring various levels of Human Robot Interaction (HRI) (Bruemmer et al., 2004). While little literature exists concerning the specific concept of UTACC, there is an abundance of literature available regarding automation and its potential future DOD applications.

Understanding the application of autonomy within the context of UTACC is important as there is a broad spectrum of what is considered to be "autonomous." Shaker and Wise (1988) provide a detailed account of the history of automation and robotics dating back to World War I. Bruemmer et al. (2004), as well as Glotzback (2004) provide useful definitions regarding automation and the metrics for measuring autonomy levels. The spectrum of autonomy ranges from direct remote control on the lower end, to fully autonomous on the upper end, wherein the unmanned system executes the mission with zero human intervention (Bruemmer et al., 2004). For the purposes of UTACC, minimizing the human input to UMS is paramount to reducing the cognitive load, but the human element must not be eliminated if UTACC is to properly function as an effective team (Rice et al., 2015). Chen and Barnes state that as vehicle autonomy increases, it is possible for operators to provide supervisory control rather than active control, providing the reduction in cognitive load sought by UTACC (2014).

With respect to UAVs, autonomy is what allows these aircraft to execute their mission following a set of instructions without operator intervention (Brungardt, 2011).

An example of "system level autonomy" is described by Fahlstrom and Gleason as an aircraft capable of "real-time interpretation of sensor information," and its ability to respond appropriately by altering the mission plan (2012, p. 129). This is particularly relevant to UTACC in the context of unmanned vehicles and their ability to be "self-governing or self-directing" as explained by Fahlstrom and Gleason (2012, p. 128). Simply put, the UAV must have a sufficient understanding of the UTACC strategic objectives to independently alter its subordinate mission when the processing of sensor data dictates a mission update in collaboration with the manned element.

Aside from literature addressing fundamental concepts and definitions associated with autonomy, the primary resources used in developing a Concept of Operations for UTACC address autonomy strictly as it relates to military applications. The overarching document which identifies the current situation and future of autonomy within the Department of Defense (DOD), called *The Role of Autonomy in DOD Systems*, was written to identify opportunities and challenges in the future implementation of autonomous vehicles in the military (DOD, 2012). UTACC exemplifies the opportunities and challenges faced by the DOD. Gustavsson and Hieb (2013) developed a concept called The Operations Intent and Effects Model. This is a unique way of implementing future Command and Control (C2) systems so as to enable the military to realize the benefits of automation without the need for continuous human input found in current C2 methodologies, a key aspect of the UTACC concept.

C. UNMANNED AERIAL VEHICLES

The following discussion will provide a historical perspective, describe system elements and elaborate on aircraft configurations common to current UAVs.

1. BACKGROUND

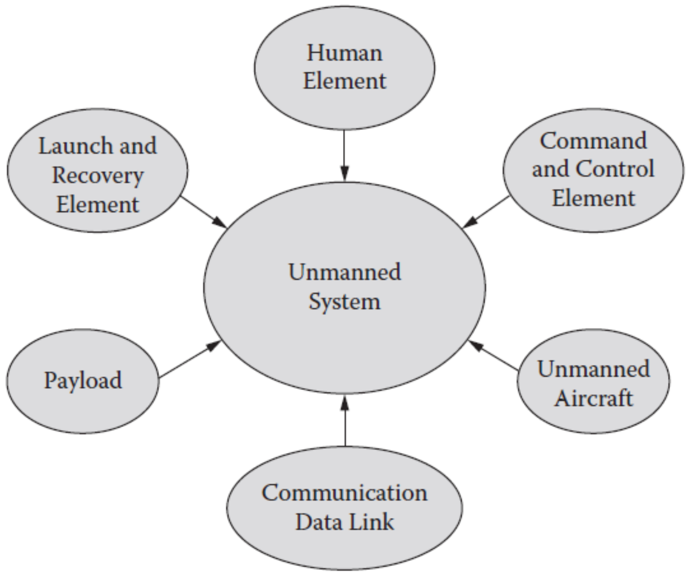
The modern concept of an unmanned aerial vehicle has experienced great changes in definition over the course of its existence. The driving factor of this evolution is rooted in the intended use of the vehicles. To that end, the development of this technology has been primarily conducted for military applications (Fahlstrom & Gleason, 2012). The historical context of modern UAVs began in the late 1800s with the use of kites for weather and photographic reconnaissance (Fahlstrom & Gleason, 2012) and the advent of gliders as experimental test beds (Jarnot, 2012). It was not until the First World War that UAVs were recognized as formal systems (Fahlstrom & Gleason, 2012). As associated technologies improved the intended use of the vehicles also evolved. So too did the names by which these aircraft were referenced. Aerial torpedoes, radio controlled aircraft, remotely piloted aircraft, remotely controlled aircraft, autonomous aircraft and drones are but some of the names used to describe what are identified now as UAVs (Jarnot, 2012).

In its most basic form, an unmanned aircraft is a remotely piloted or autonomous vehicle capable of mimicking the maneuvers of a manned craft in airborne flight (Jarnot, 2012). Fahlstrom and Gleason simplify this further, stating that any aircraft capable of flying without a pilot, excluding missiles, may generically be called a UAV (2012).

2. SYSTEM ELEMENTS

Modern UAVs are complex systems comprised of various system elements. Together, they constitute a complete unmanned aircraft system, or UAS (Brungardt, 2011). System elements may include but are not limited to: the human element, command and control elements, communications and data link elements, the payload, and the vehicle itself (Brungardt, 2011). Figure 1 summarizes a common UAS element architecture.

Figure 1. Elements of an Unmanned Aircraft System



Source: Brungardt, J. (2011) *Introduction to Unmanned Aircraft Systems* R. K. Barnhart, S. B. Hottman, D. M. Marshall, and E. Shappee, (eds). Boca Raton, FL: CRC Press.

a. Command and Control

A method of command and control is a critical element of any UAS. The concept of command and control with respect to UAS is broad and includes aspects of ground control stations, operating systems, communications and data links, and autopilot. The autopilot provides direct control over the physical flight path of an UAV. It is an electronic control system capable of stabilizing the aircrafts' flight characteristics (Brungardt, 2011). As such it employs a feedback loop operation to validate or correct flight performance parameters to the desired state (Fahlstrom & Gleason, 2012). It does this by taking measurements of the actual state of the aircraft with respect to attitude, airspeed, altitude, and flight path and compares them to the desired flight profile. Any deviation from this profile can then be corrected with electronic signals to actuators manipulating the flight control surfaces of the aircraft (Fahlstrom & Gleason, 2012). The other aspects of command and control are all working to provide inputs or updates to the desired airborne state of the vehicle, allowing the autopilot to make appropriate corrections to physically guide the system.

b. Payload

The employment of onboard sensors or weapons systems in the execution of a prescribed mission is the primary purpose of DOD UAVs. The term “payload” is somewhat ambiguous with respect to UAS in that it can be applied to all equipment, avionics and even fuel supply carried onboard the aircraft (Fahlstrom & Gleason, 2012). For the purposes of this study, Fahlstrom and Gleason provide a better interpretation of payload which excludes the onboard equipment required for basic flight, launch and recovery operations of the vehicle (2012). The term payload is then reserved for the equipment that is added to a vehicle with the express purpose of conducting some operational mission (Fahlstrom & Gleason, 2012). Generally this mission consists of reconnaissance, electronic warfare, or weapons delivery (Fahlstrom & Gleason, 2012). Subsequently, the payload may consist of surveillance or sensing equipment, communications relay nodes, cargo, weapons or any combination therein (Brungardt, 2011). Finally, payload size, weight and power requirements are of critical importance when placed in the context of the vehicle from which they will be operating.

c. Launch and Recovery Equipment

Unmanned aircraft systems have a varying array of launch and recovery methods. Some systems have elaborate launch and recovery equipment and procedures (Brungardt, 2011). These may include catapult systems and arresting equipment such as netting or wire recovery devices, or self-recovering mechanisms such as a parachutes or parafoils (Fahlstrom & Gleason, 2012). Other UAS require virtually no launch and recovery equipment at all, as is the case with many VTOL systems. Conventional takeoff and landing techniques on prepared sites are quite common as well, and encompass the majority of larger UAVs in operation today (Brungardt, 2011).

d. Ground Support Equipment

As with launch and recovery equipment, the ground support equipment (GSE) element plays a vital role in the operational context of UAS employment. The logistical footprint of this equipment varies dramatically between the multitudes of systems in use today. Types of GSE include test and maintenance equipment, spare part supply, fuel and refuel equipment and supply, ground handling equipment to move the aircraft as necessary and generators to power all of these associated components (Fahlstrom & Gleason, 2012). Mobility is also critical to consider, along with the number of personnel required to move, maintain and operate the vehicle (Fahlstrom & Gleason, 2012). It is important to note that even for relatively small UAS, the logistical footprint can be substantial (Fahlstrom & Gleason, 2012).

e. Human Element

Though there is a strong desire to move towards ever more autonomous systems, the human element remains a critical component of any UAS (Brungardt, 2011). As technologies continue to advance, the human element will continue to diminish though it can never be eliminated. Current UAVs require a pilot, sensor operators and ground crew to execute their missions (Brungardt, 2011). Reducing these manning requirements while increasing vehicle autonomy is crucial to the UTACC concept (Rice et al., 2015).

3. CONFIGURATIONS

When characterizing aircraft configurations, popular literature generally describes vehicles in three categories: fixed wing, vertical takeoff and landing (VTOL) and lighter-than-air (LTA).

a. Fixed Wing

As the name suggests, fixed wing vehicles are generally configured with a fuselage, wing and empennage. In some cases, these fixed wing aircraft were of a flying wing design and had minimal fuselage and empennage. Fixed wing aircraft generally provide longer flight endurance, greater ranges, and operations at higher altitudes (Brungardt, 2011). While these vehicles often maximize airborne performance qualities as described previously, this performance comes at the expense of greater logistical requirements (Brungardt, 2011). These aircraft require a runway or catapult for takeoff and either a runway or mechanical recovery system for landing imposing operational restrictions on mission capability (Brungardt, 2011).

b. VTOL

VTOL aircraft are characterized as those vehicles that primarily employ lift and propulsion through a main rotor or ducted fan design, and yaw control through a mechanism such as a tail-rotor or fenestron. Since these platforms do not require a prepared surface or other mechanical devices for launch and recovery, they generally have a smaller logistical penalty (Brungardt, 2011). Additionally, VTOL aircraft have the ability to hover over a spot, providing greater operational flexibility (Brungardt, 2011).

c. LTA

Two categories generally comprise the lighter-than-air vehicle classification: conventional and hybrid airships (Assistant Secretary of Defense for Research and Engineering, 2012). Conventional airships utilize a lifting gas such as helium to provide buoyancy (Assistant Secretary of Defense for Research and Engineering, 2012). A hybrid airship uses the combination of buoyant gas, aerodynamic shapes, and some form of propulsive device exemplified by dirigibles or blimps (Assistant Secretary of Defense for Research and Engineering, 2012). Current DOD applications of these aircraft include tethered aerostats for ISR missions (Assistant Secretary of Defense for Research and Engineering, 2012).

4. DOD GROUPS

The DOD differentiates UAVs by weight, airspeed and operating altitude and categorizes these aircraft into five groups based on these metrics, summarized in Figure 2. Group 1 aircraft have a maximum gross takeoff weight of less than 20 pounds with an airspeed less than 100 knots and an operating altitude less than 1,200 feet above ground level (AGL). Aircraft categorized as Group 2 have a maximum gross takeoff weight range from 21 to 55 pounds and operate below 3,500 feet AGL and less than 250 knots. Group 3 aircraft are less than 1,320 pounds and operate at any airspeed below 18,000 feet mean sea level (MSL). Group 4 aircraft are identified by a maximum gross takeoff weight greater than 1,320 pounds and operate at any airspeed below 18,000 feet MSL. Finally, Group 5 aircraft are solely categorized by their ability to operate at altitudes greater than 18,000 feet MSL.

Figure 2. DOD UAS Categories

UAS Category	Max Gross Takeoff Weight	Normal Operating Altitude (ft)	Airspeed
Group 1	<20 pounds	<1200 above ground level (AGL)	<100 knots
Group 2	21–55 pounds	<3500 AGL	< 250 knots
Group 3	<1320 pounds	<18,000 mean sea level (MSL)	
Group 4	>1320 pounds		Any airspeed
Group 5		>18,000 MSL	

Note: If a UAS has even one characteristic of the next higher level, it is classified in that level.

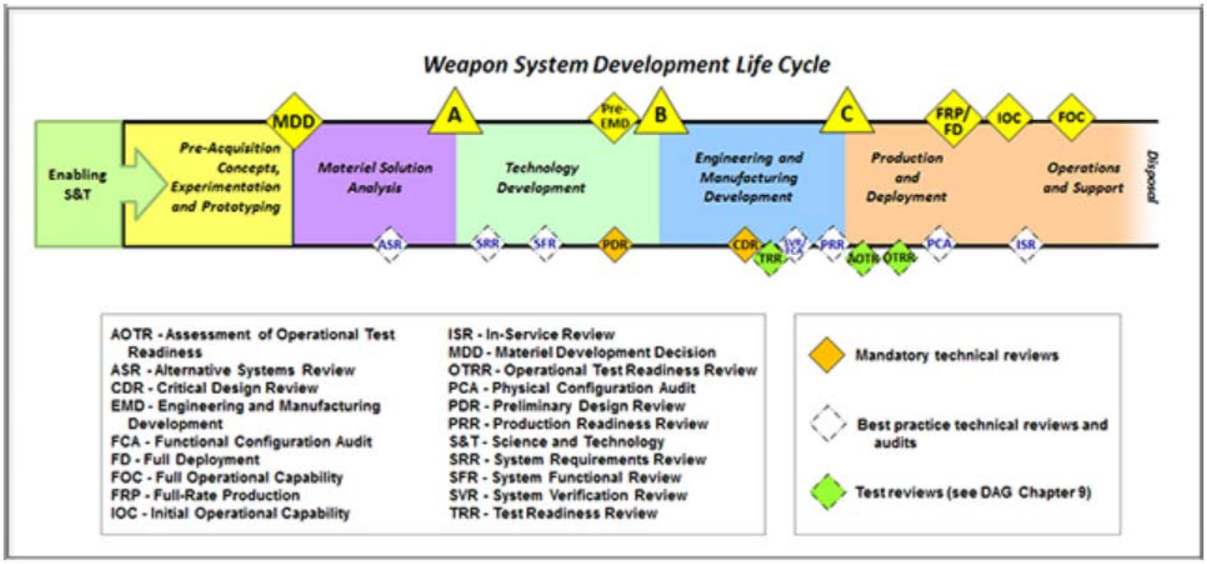
Source: Jarnot, C. (2012). *Introduction to Unmanned Aircraft Systems* R. K. Barnhart, S. B. Hottman, D. M. Marshall, and E. Shappee (eds.). Boca Raton, FL: CRC Press. Retrieved from http://www.crcnetbase.com.libproxy.nps.edu/isbn/9781439835203

D. DEPARTMENT OF DEFENSE ACQUISITION SYSTEM

The Defense Acquisition System (DAS) is responsible for the management of the technological, programmatic and product support investment in support of the Department of Defense (Secretary of Defense for Acquisition, Technology, and Logistics, 2007). Further, the objective of the DAS is to acquire products that measurably improve mission capability while satisfying the needs of the end user (Secretary of Defense for Acquisition, Technology, and Logistics, 2007). The Joint Capabilities Integration and Development System (JCIDS), under the auspices to the Chairman of the Joint Chiefs of Staff (JCS), employs a systematic method "for identifying, assessing, and prioritizing gaps in joint warfighting capabilities and recommending potential solution approaches to resolve these gaps" (Defense Acquisition University [DAU], 2013, p. 6). Through this process, the JCIDS develops an Initial Capabilities Document (ICD) (DAU, 2013).

This ICD is published in order to support the materiel development process (Brown, 2010). The ICD specifically provides a definition of a capability gap within an operational concept (Brown, 2010). According to the DAU (2013), the systems engineering process for the acquisition of a weapon system can be seen through the life-cycle flow chart (Figure. 3).

Figure 3. Weapon System Development Life Cycle



Source: Defense Acquisition University. (2013). Defense Acquisition Guidebook. Retrieved from https://acc.dau.mil/docs/dag_pdf/dag_complete.pdf

Within this systems engineering approach to the acquisition of a weapon system are five phases, including the material solution analysis (MSA) phase and a subordinate analysis of alternatives (AoA) (DAU, 2013). Due to the immaturity of the UTACC program, this study focuses only on the MSA phase described in the DAS.

The MSA phase is designed to determine the appropriate material solution to satisfy an identified capability need (DAU, 2013). As mentioned by the Office of Aerospace Studies (2013), during the MSA phase, capability gaps are assessed and mitigated within the context of the ICD developed for a given program. Activities completed during the MSA include an evaluation of each potential alternative in the form of an AoA (DAU, 2013).

An AoA is an important part of the MSA for any major DOD acquisition program. According to the DAU (2013), an AoA is intended to evaluate operational effectiveness, suitability to mitigating capability gaps and life-cycle costs of alternative solutions to an identified need. Furthermore, the analysis must consider the trade-offs between cost, schedule and performance of each alternative (DAU, 2013).

In order to effectively analyze alternative solutions, the DAU encourages the development of a comprehensive AoA study plan (DAU, 2013). The recommended study plan includes an introduction and ground rules which will identify the purpose and provide context to the analysis (DAU, 2013). Additionally, the study plan calls for the evaluation of both viable and nonviable alternatives in the context of operational and sustainment concepts (DAU, 2013). Also critical to the study plan are evaluations of mission effectiveness and cost effectiveness (DAU, 2013) which provides for a quantitative method for comparing alternatives. Each of these steps in the study plan allows for the development of characteristics and associated metrics by which to measure them in order to determine a suitable alternative.

E. CHAPTER CONCLUSION

Establishing this academic background is critical to systematically evaluate potential aircraft within the context of the UTACC CONOPS. This literature review establishes a solid foundation to develop a systematic analysis method, and the metrics required to analyze UAVs suitable for the UTACC program.

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III. RESEARCH METHODOLOGY

The authors of the concept of operations (CONOPS) thesis explicitly state that their focus was not on specific hardware components of the system but rather on information exchange requirements (IER) (Rice et al., 2015). Conversely, the authors of this thesis are the first to establish specific vehicle requirements for the UTACC program. This chapter establishes a systematic approach to analyzing the functional characteristics of the aircraft and describes the metrics utilized to determine an appropriate aircraft that supports the UTACC concept.

A. MATERIAL SOLUTION AND ANALYSIS OF ALTERNATIVES

Determining the appropriate UAV platform for the UTACC program requires a thorough examination of the needs of the program. The analysis of alternatives (AoA) approach is ideal for this examination, but certain limitations in the available documentation and aircraft data require that the approach be adapted. As stated in the previous chapter, the AoA ensures potential materiel solutions that could satisfy validated capability requirement(s) and supports a decision on the most cost effective solution to meeting the capability requirement(s) (Secretary of Defense for Acquisition, Technology, and Logistics, 2015). The AoA identifies "a wide range of solutions that have a reasonable likelihood of providing the needed capability" (Secretary of Defense for Acquisition, Technology, and Logistics, 2015, p. 125). Specifically, an AoA is "an analytical comparison of the operational effectiveness, suitability, risk, and life cycle cost" of proposed materiel solutions to gaps and shortfalls in operational capability (OAS, 2013 p. 7). AoAs document the rationale for identifying and recommending a preferred solution or solutions to the identified shortfall(s) (OAS, 2013).

As described in Chapter II of this study, an Initial Capabilities Document (ICD) is a critical pillar to the execution of an AoA. Because UTACC is not an acquisition category (ACAT) I or IA program of record as established by the DODI 5000.02, no ICD exists to guide this analysis (Secretary of Defense for Acquisition, Technology, and Logistics, 2015). In the absence of an ICD, the CONOPS thesis by Rice et al. (2015)

established the baseline capabilities requirements of the UAVs. Due to a lack of available information concerning life cycle costs and potential developmental program risks, this study only evaluated vehicles based on known capabilities and characteristics.

B. RESEARCH DATABASE POPULATION

Despite the variety of unmanned aircraft in the DOD inventory, the results of the material solution analysis determined that none presently meet all of the requirements established under the UTACC CONOPS for an operationally suitable UAV solution. Within the DOD inventory, the analysis did identify the Honeywell RQ-16 T-Hawk as a vehicle that could potentially be utilized to further UTACC research, systems and component development, testing and evaluation based upon metrics that will be described later in this chapter.

In the absence of a suitable aircraft in the DOD inventory, the authors examined commercially available aircraft. The authors of this study developed a comprehensive database of aircraft from various unclassified open sources such as *Jane's All the World Aircraft: Unmanned* (n.d.), *Shephard Unmanned Vehicles Handbook* (Kemp, 2015), and manufacturer websites. This research yielded an initial database containing over 600 aircraft. After reviewing these 600 aircraft, the authors further reduced those evaluated by eliminating aircraft identified as aerial targets and those categorized Group 4 and Group 5 as described in Chapter II. By direction of the Marine Corps Warfighting Laboratory (MCWL), the vehicles evaluated were further restricted to those manufactured by companies based in the United States. Finally, various assumptions are made regarding the size, weight, and capability of the aircraft based on the CONOPS established by Rice et al. (2015). The resulting database for this study contains 81 aircraft, which were evaluated based on criteria detailed later in this chapter.

C. EVALUATION CRITERIA AND METRICS DEVELOPMENT

As mentioned previously in this chapter, the authors of this study utilized the CONOPS developed by Rice et al. (2015) as the ICD for developing aircraft evaluation criteria. The following discussion clearly identifies the critical categories by which each aircraft was evaluated.

Unmanned aerial vehicles can be evaluated using any number of characteristics. Based on the CONOPS developed by Rice et al. (2015), this study uses three categories, physical dimensions, performance and sensor and payload capabilities, as the criteria for evaluating potential aircraft. Each of these categories was further divided into subcategories. The physical dimensions of each aircraft were broken into length, wingspan/rotor diameter and weight subcategories. The performance category was broken into endurance, range and ceiling subcategories. Finally, the sensor and payload category was broken into modularity, sensor options and number of sensor subcategories. This is illustrated in Table 1.

Table 1. Evaluation Criteria

Critical Categories and Subcategories		
Physical Dimensions	**Performance**	**Sensor**
Length	Endurance	Modularity
Wingspan / Rotor diameter	Range	Sensor Options
Weight	Ceiling	Number of Sensors

In order to quantify the categories of each aircraft, the authors assigned a priority value and ranking value to each subcategory. The priority value was assigned based on the relative importance of that subcategory to UTACC. This determination was interpreted through the lens of the CONOPS developed by Rice et al. (2015). The ranking value of each subcategory was based on the aircraft's specific capabilities. The product of the priority value and ranking value resulted in a score assigned to each subcategory for each aircraft. Finally, the sum of each subcategory score resulted in an overall score for each aircraft in each category.

In addition to the previously described scored characteristics, the study also evaluated launch and recovery method and operating system functionality for each aircraft. With respect to the launch and recovery method, the authors determined that the aircraft must be capable of vertical takeoff and landing (VTOL), to be described later in this chapter. Similarly, OS and autopilot functionality were determined to be outside the scope of this study but merited consideration as describe later in this chapter.

1. CHARACTERISTICS EVALUATED AND SCORED

This section discusses the specific evaluation criteria and associated critical metrics.

a. Physical Dimensions

Rice et al. (2015) describe a small dismounted unit employing several vehicles in the UTACC CONOPS, specifically identifying an Air Carrier (AC) and UAV as playing critical roles within UTACC. The AC is described as a ground vehicle capable of transporting, launching, recovering and supporting multiple UAVs (Rice et al. 2015). With this concept established, MCWL proposed utilizing the available Ground Unmanned Support Surrogate (GUSS) vehicle based on the Polaris MVR 700 series chassis to serve as the developmental AC for UTACC. Subsequently, any UAV evaluated for the purposes of further developing the UTACC concept should only be considered if it is appropriately sized to operate with the GUSS.

(1) Weight

The weight subcategory was given the highest priority value of five due to the relative importance assigned by the authors to this characteristic. The ranking value for the weight subcategory was determined using the DOD Unmanned Aerial System Categories (Figure 4) (Joint Chiefs of Staff [JCS], 2014) and the DOD Design Criteria Standard for Human Engineering (Figure 5) (MIL-STD-1472F) (2003). The authors limited the vehicles examined to those satisfying Group I, Group II and Group III aircraft based on established DOD criteria. These vehicles have a gross weight less than 1,320 lbs. and can be more readily transported by a small dismounted unit.

Figure 4. DOD Unmanned Aerial System Categories

UAS Category	Max Gross Takeoff Weight	Normal Operating Altitude (ft)	Airspeed
Group 1	<20 pounds	<1200 above ground level (AGL)	<100 knots
Group 2	21–55 pounds	<3500 AGL	< 250 knots
Group 3	<1320 pounds	<18,000 mean sea level (MSL)	
Group 4	>1320 pounds		Any airspeed
Group 5		>18,000 MSL	

Note: If a UAS has even one characteristic of the next higher level, it is classified in that level.

Source: Brungardt, J. (2011) *Introduction to Unmanned Aircraft Systems* R. K. Barnhart, S. B. Hottman, D. M. Marshall, and E. Shappee, (eds.). Boca Raton, FL: CRC Press.

The authors further limited the weight of each vehicle to those that could be moved by two personnel. Ideally, the authors concluded that the vehicle should be man portable to reduce the impact on the unit's personnel resources. The DOD Design Criteria Standard for Human Engineering (MIL-STD-1472F) establishes the maximum load size an individual can lift (Figure 5). Accordingly, the authors gave greater precedence to vehicles with a weight less than 174 lbs, the maximum allowable load for two men to lift an object to a 3-foot surface. Based on this information, aircraft weighing less than 87 pounds were assigned a ranking value of six. Aircraft weighing between 87 pounds and 174 pounds were assigned a ranking value of four and those aircraft weighing more than 174 pounds were assigned a ranking value of two.

Figure 5. Maximum Design Weight Limits

HANDLING FUNCTION	POPULATION	
	Male and Female	Male Only
A. Lift an object from the floor and place it on a surface not greater than 152 cm (5 ft) above the floor.	16.8 kg (37 lb)	25.4 kg (56 lb)
B. Lift an object from the floor and place it on a surface not greater than 91 cm (3 ft) above the floor.	20.0 kg (44 lb)	39.5 kg (87 lb)
C. Carry an object 10 m (33 ft) or less.	19.0 kg (42 lb)	37.2 kg (82 lb)

Source: Department of Defense. (2003). *Design Criteria Standard: Human engineering* (MIL-STD-1472F). Washington, DC: Author. Retrieved from http://www.dtic.mil/dtic/tr/fulltext/u2/a550252.pdf

(2) Footprint

Additionally, the authors compared vehicles based on their footprint, defined as length and span or rotor diameter. This factor is driven by the assumed platform space that the GUSS AC will accommodate, an area approximately 110 inches long by 60 inches wide. Vehicles with a smaller footprint provide greater flexibility to the AC in the number of vehicles it is capable of carrying. Accordingly, smaller aircraft are assigned a higher ranking value. Aircraft with a footprint less than two feet were assigned a ranking value of six. Aircraft with a footprint between two feet and eight feet were assigned a ranking value of four. Aircraft with a footprint greater than eight feet were assigned a ranking value of two. The priority and ranking values assigned to physical dimension category are illustrated in Table 2.

Table 2. Physical Dimension Ranking Values

	PRIORITY VALUE	**RANKING VALUE**		
		6	4	2
Length	3	<2 ft	2–8 ft	>8 ft
Span/Rotor diameter	3	<2 ft	2–8 ft	>8 ft
Weight	5	<87 lbs	87–174 lbs	>174 lbs

b. Performance

Within this performance category, the subcategories of endurance, range and ceiling were evaluated. While there may be an instance where long range surveillance is desired, the small size of a UTACC unit coupled with the limitations inherent in a dismounted unit's ability to move long distances through the battlespace led the authors to minimize the relative importance of the range subcategory.

(1) Endurance

While it could be said that range and endurance are similar, the ability to stay aloft providing persistent surveillance was much more important than a vehicles ability to surveil a target at great distance. The argument for this position is based on the concepts established by Rice et al. (2015) defining the makeup of a UTACC unit. Consequently, endurance was determined to be the most important subcategory while range was considered the least important. Due to this assessment of the CONOPS the authors of this study assigned a priority value of five to the endurance subcategory and a priority value of three for both ceiling and range subcategories.

With this interpretation of the CONOPS, the authors assigned a ranking value of six to aircraft with endurance greater than eight hours. Aircraft with endurance between two hours and eight hours were assigned a ranking value of four and aircraft with endurance less than two hours were assigned a ranking value of two.

(2) Ceiling

Based on the need of the UTACC unit to operate in multiple and disparate environments, ceiling was considered an important metric. For purposes of this study, ceiling is defined as the highest altitude at which an aircraft can operate. High density altitude and operations in mountainous terrain will require the aircraft to be able to operate at high altitudes in order to support the UTACC ground element. Within this construct, aircraft with a ceiling greater than 10,000 feet mean sea level (MSL) were assigned a ranking value of six. Aircraft with a ceiling between 5,000 feet MSL and

9,999 feet MSL were assigned a ranking value of 4 and aircraft with a ceiling less than 5,000 feet MSL were assigned a ranking value of two.

(3) Range

With respect to range, many of the vehicles reviewed have multiple configuration options. The performance data results are sometimes limited by the configuration that the vehicle is tested in (for example, active line-of-sight communications link), and a specific range would be dependent on numerous variables not calculable or available from the manufacturer. These vehicles still remain relevant to this study so long as the ability to incorporate an autonomous flight control system exists. Based on the data available for evaluations, the authors assigned a ranking value of six to aircraft with a range greater than 200 nautical miles (NM). Aircraft with a range between 100 NM and 199 NM were assigned a ranking value of 4 and aircraft with a range less than 100 NM were assigned a ranking value of 2. These priority and ranking values of performance characteristics are summarized in Table 3.

Table 3. Performance Characteristic Ranking Values

	PRIORITY VALUE	**RANKING VALUE**		
		6	4	2
Endurance	5	>8 hrs	2-8 hrs	< 2 hrs
Range	3	>200 NM	100-199 NM	< 99 NM
Ceiling	3	>10000 MSL	5000-9999 MSL	< 5000 MSL

c. Sensors

Sensor capabilities are the primary purpose for employing an unmanned aircraft in the UTACC concept. While specific payloads and sensors were not evaluated, the payload capability and breadth of sensor options for each vehicle was. Accordingly, the variety of sensors, quantity of sensors and the modularity of sensors were evaluated. The modularity and variety subcategories were assigned a higher priority value based on the authors’ interpretation of UTACC mission requirements. It must be stated that the sensor capabilities discussed in this section are those required for the UTACC mission, and not those required for the basic flight operation of the aircraft platform. Some examples of flight related sensors are pitot-static sensors, global positioning system (GPS), or radar altimeters (RADALT).

(1) Modularity

The authors of this study determined that providing the ground unit with the ability to quickly configure the aircraft with different sensors depending on mission needs was more important than the aircrafts' ability to carry multiple sensors simultaneously. Accordingly, the authors assigned a priority value of five to aircraft with a modular sensor capability. In addition, aircraft with the ability to carry a variety of different sensors were also given a priority of five. Finally, aircraft capable of carrying multiple sensors simultaneously were assigned a priority value of one.

Many vehicles evaluated carried fewer sensors but were designed with a modular architecture allowing for rapid changes to sensor configuration providing greater flexibility to UTACC unit operations. Because of this, the authors assigned aircraft with a modular sensor capability a ranking value of six. If the aircraft did not have a modular sensor capability it was assigned a ranking value of two.

(2) Sensor Options

Providing UTACC units with a variety of sensor options with capabilities such as electro-optical (EO), infrared (IR), and light detection and ranging (LIDAR), is essential. Aircraft with a greater sensor variety were given a higher ranking value. Therefore, aircraft capable of operating more than four sensor types were assigned a ranking value of six. Aircraft capable of operating between two and four sensor types were assigned a ranking value of four and aircraft only capable of operating one sensor type were assigned a ranking value of two.

(3) Number of Sensor Mounts

Aircraft with the ability to mount more than two sensors simultaneously were assigned a ranking value of six. Aircraft with the ability to mount two sensors simultaneously were assigned a ranking value of 4 and aircraft only capable of mounting one sensor were assigned a ranking value of two. The priority and ranking values assigned to the sensor category are illustrated in Table 4.

Table 4. Sensor Characteristic Ranking Values

	PRIORITY VALUE	RANKING VALUE		
		6	4	2
Modularity	5	Yes	-Null-	No
Sensor Options	5	>4	2-4	1
Number of Sensor Mounts	1	>2	2	1

2. CHARACTERISTICS EVALUATED BUT NOT SCORED

Two additional characteristics, launch and recovery method and autopilot and operating systems, were considered during this evaluation but were not quantified.

a. Launch and Recovery

The tactical requirements of the UTACC program dictate a need for precision launch and recovery capabilities. Based on the CONOPS established by Rice et al. (2015), the authors of this study determined that aircraft capable of VTOL are the only viable options to UTACC. Many of the vehicles capable of longer endurance were designed with a traditional fixed wing configuration. These aircraft require a runway or mechanical apparatus for launch and recovery. Examples of a mechanical apparatus include catapults, nets and wire-and-hook devices for launch and recovery respectively. While included in the study, aircraft requiring a prepared runway or mechanical apparatus for launch and recovery were deemed impractical and therefore not considered for recommendation.

It is the authors' contention that aircraft selected for the UTACC program be capable of VTOL to ensure the ability to land and recover to a spot. As mentioned in Chapter II, UAVs are generally classified as fixed wing, VTOL, or LTA. To further differentiate between vehicles that exhibit the qualities of both fixed wing and VTOL aircraft, the authors developed the hybrid classification. Hybrid aircraft are capable of VTOL for launch and recovery and transition to traditional wing-borne flight for cruise and extended loiter. Aircraft in this category were varied in specific design and capability.

b. Operating System and Autopilot

Operating systems (OS) and autopilot systems provide an interface between the aircraft and UTACC. OS flexibility is important to the development of UTACC; hence the authors examined a vehicle's ability to employ an open-source or commercially available system. Additionally, the authors evaluated vehicles requiring proprietary software solutions for operation against open-source solutions where the ability of software to be independently programmed by the users exists. Due to the complexity of quantifying the capabilities of these systems, the authors contend that evaluating their specific capabilities and characteristics are beyond the scope of this study. Therefore, this study did not integrate OS and autopilot functionality into the final determination of evaluated characteristics within the AoA.

D. OPTIONS DEVELOPMENT AND CHAPTER CONCLUSIONS

This chapter established a systematic approach to analyzing the functional characteristics of the aircraft. By evaluating each aircraft based on the established categories and subcategories, an appropriate aircraft that supports the UTACC concept can be recommended. The following chapters will show the practical application of the AoA process described in this chapter and provide recommendations of suitable aircraft for UTACC.

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IV. UAV ANALYSIS OF ALTERNATIVES

Employing the methodology outlined in Chapter III, this chapter will describe the nine aircraft that satisfy the evaluation criteria developed for this study. These evaluation criteria have been established based on the operational concepts developed by Rice et al. (2015). The resulting aircraft are capable of vertical takeoff and landing (VTOL), provide a useful sensor payload greater than two pounds and a minimum endurance of 45 minutes.

A. SELECTION CHARACTERISTICS: OPERATIONAL CONTEXT

As mentioned in Chapter III, the authors of this study determined physical dimensions, performance, and sensor capabilities to be the most important characteristics for evaluation. Specifically, aircraft weight, endurance and sensor variety and modularity are identified as the critical subcategories within the aforementioned categories based on the concepts of operation (CONOPS) document (Rice et al., 2015). Based on the scoring methodology established in Chapter III, the maximum score an aircraft could earn is 198. Additionally, the concept of the Air Carrier (AC) and its characteristics established by Rice et al. (2015) led the authors of this study to narrow the evaluation of potential aircraft to those with VTOL capability. While fixed wing aircraft generally provide greater airborne mission capabilities, these aircraft are ultimately excluded from this study due to the requirement of a runway or mechanical launch and recovery mechanism imposing prohibitive logistical limitations on the UTACC unit. Further, the authors determined that some aircraft were unsuitable for an operational deployment but could provide value to the research, development, test and evaluation (RDT&E) phase of the UTACC program.

B. UAV POPULATION AND DESCRIPTION

The following discussion will include a description of each aircraft that satisfied the evaluation criteria established by the authors of this study. The Group 1 aircraft evaluated, those with a maximum takeoff weight (MTOW) of less than 20 pounds, each satisfy the criteria described in Chapter III. Due to their diminutive size, Group 1 vehicle endurance and sensor capabilities are less impressive than some of the larger aircraft. Consequently, it is the authors' contention that Group 1 aircraft are generally suitable for RDT&E. The largest number of vehicles evaluated for this analysis fall into the Group 2 and 3 classifications. Aircraft in these groups have a MTOW between 21 and 55 pounds (Group 2) and between 56 and 1320 pounds (Group 3). These aircraft offer significantly more mission capability than those found in Group 1. Group 2 and 3 aircraft offer higher performance characteristics that accommodate a broad range of sensors and an expanded variety of mission profiles which make these aircraft suitable to both UTACC RDT&E and operational applications. Table 5 presents vehicles that satisfied the evaluation criteria developed by the authors of this study.

Table 5. Vehicles Satisfying Evaluation Criteria

Group 1 (<20 lbs.)	**Group 2 (21–55 lbs.)**	**Group 3 (56-1320 lbs.)**
Honeywell International RQ-16 T-Hawk	Aerovel Flexrotor	Martin UAV V-Bat
BirdsEyeView Firefly6	Latitude Engineering HQ-40	Scion S-200 Weasel
Adaptive Flight Hornet Maxi	Dragonfly Pictures DP-6X Whisper	Latitude Engineering HQ-60

1. Honeywell RQ-16 T-Hawk

The Honeywell RQ-16 T-Hawk (see Figure 6) is the highest scoring vehicle among those evaluated in Group 1 with an overall score of 124. These evaluation scores are summarized in Table 6. A number of these aircraft are currently in the custody of the Naval Surface Warfare Command (NSWC) and are known to MCWL personnel. With cost as an independent variable, the authors of this study believe the RQ-16 is the ideal candidate for the RDT&E phase of the UTACC program.

The RQ-16 is the highest rated aircraft in both the physical and sensor categories among Group 1 aircraft. The RQ-16 earned a sensor and payload score of 42 based on the modularity and quantity of sensors the aircraft is capable of employing. Further, the RQ-16 scored among the highest in the physical dimensions category based on the aircraft's small size and light weight.

Figure 6. Honeywell RQ-16 T-Hawk

Source: Honeywell International RQ-16 T-Hawk. (n.d.). Retrieved August 21, 2015, from http://www51.honeywell.com/aero/common/documents/myaerospacecatalog-documents/Defense_Brochures/T-Hawk_MAV.pdf

The RQ-16 is a small ducted fan aircraft. It subsequently has numerous limitations which are reflected in the performance score, specifically limited endurance and range. The RQ-16 has a demonstrated endurance of 45 minutes. For the purposes of test and evaluation, this endurance may be sufficient. However, in an operational environment such a short endurance will likely impose undue burden upon the UTACC system, requiring more frequent launch, recovery and servicing operations.

Table 6. Honeywell RQ-16 T-Hawk

Overall Score: 124		
Physical Dimensions: 54	**Performance: 28**	**Sensor: 42**
Length:12	Endurance:10	Modularity: 30
Wingspan / Rotor Diameter:12	Range: 6	Sensor Options: 10
Weight: 30	Ceiling: 12	Number of Sensors: 2

2. BirdsEyeView Aerobotics FireFly6

The BirdsEyeView Aerobotics FireFly6 (see Figure 7) is a small commercially available tilt-rotor aircraft with a 2.5 pound useful payload. Due to its small size and open source operating system it provides a cost effective and flexible option for the RDT&E phase of the UTACC program. In addition, the FireFly6 is in production and can be procured quickly at reasonable cost. The evaluation scores for the FireFly6 are summarized in Table 7.

Figure 7. BirdsEyeView Aerobotics FireFly6

Source: BirdsEyeView Aerobotics. (n.d.). Retrieved July 12, 2015, from http://www.birdseyeview.aero/products/firefly6

The FireFly6 earned an overall score of 108, the lowest of all Group I aircraft. Despite the overall score, it has many attributes that make it a promising candidate for near term UTACC research. In addition to being commercially available for less than $2000, the FireFly6 is three feet long with a five foot wingspan and weighs only nine pounds. While this earns the aircraft high marks for the physical score, it is the source of some of its weaknesses. Because of its small size the FireFly6 has a limited array of sensors, a relatively short endurance (45 minutes) and may be more susceptible to environmental conditions such as gusting winds and high density altitude. Furthermore, the vehicle is exclusively battery powered and consequently has limited electrical resources available for the sensor suite and flight operations.

Despite these shortcomings, the authors of this study have identified this vehicle as having an excellent balance of cost and capability making it a highly suitable vehicle for the RDT&E phase. The vehicle includes a modular sensor bay which can provide MCWL the ability to increase the number of batteries for greater performance, or reduce the number of batteries to increase sensor payload. While the variety of sensors available for the aircraft is limited the potential options for experimentation are numerous.

Table 7. BirdsEyeView Firefly6

Overall Score: 108		
Physical Dimensions: 54	**Performance: 28**	**Sensor: 26**
Length: 12	Endurance: 10	Modularity: 10
Wingspan / Rotor Diameter: 12	Range: 6	Sensor Options: 10
Weight: 30	Ceiling: 12	Number of Sensors: 6

3. Adaptive Flight Hornet Maxi

The Adaptive Flight Hornet Maxi (see Figure 8) is a gasoline powered rotary wing helicopter with a traditional tail rotor for yaw control. The Hornet Maxi earned an overall score of 120 based primarily on its small size and variety of sensors. A full summary of evaluation scores for the Hornet Maxi can be found in Table 8. This aircraft earns a sensor score of 32 based on its ability to carry an electro-optical (EO) camera, infrared (IR) camera or multiple high resolution imaging sensors (Adaptive Flight, n.d.). The Hornet Maxi is 4 feet long with a 4.4 foot rotor diameter and 8.8 pound max takeoff weight (Adaptive Flight, n.d.). These physical characteristics rate highly in this study.

Figure 8. Adaptive Flight Hornet Maxi

Source: Adaptive Flight Hornet Maxi. (n.d.). Retrieved July 6, 2015, from http://www.adaptiveflight.com/products/maxi/hornet-maxi-introduction/hornet-maxi-specs/

As with most of the traditional rotary wing aircraft evaluated, the Hornet Maxi suffers from short endurance, 45 minutes, which limits its operational suitability to the UTACC program. Still, this vehicle is a viable option for the RDT&E phase of the UTACC program based on the variety of sensors.

Table 8. Adaptive Flight Hornet Maxi

Overall Score: 120		
Physical Dimensions: 54	**Performance: 34**	**Sensor: 32**
Length:12	Endurance: 10	Modularity: 10
Wingspan / Rotor Diameter: 12	Range: 6	Sensor Options: 20
Weight: 30	Ceiling: 18	Number of Sensors: 2

4. Aerovel Flexrotor

The Aerovel Flexrotor (see Figure 9) presents a unique combination of performance characteristics and capabilities that fit well with the needs of the UTACC program. The evaluation scores for Aerovel Flexrotor are found in Table 9. With an innovative design employing a traditional rotor system to launch and recover from a tail-sitting position, the Flexrotor is capable of operations in confined areas and earned an overall score of 136. The Flexrotor’s performance is the vehicles greatest attribute, and most responsible for the assigned overall score. With a demonstrated endurance of more than 40 hours, Flexrotor is by far the most capable within this subcategory. While the authors consider range and ceiling to be of less importance to the UTACC program, the Flexrotor also scored highly in these subcategories.

Figure 9. Aerovel Flexrotor

Source: Aerovel Flexrotor. (n.d.). Retrieved July 12, 2015, from http://aerovelco.com/production/wp-content/uploads/2014/11/flexrotor_VTOL.jpg

Though the performance and physical dimensions of the Flexrotor are commendable, the aircrafts’ sensor capability is less impressive. The vehicle is capable of both EO and IR sensors; it is not capable of employing both simultaneously. According to the manufacturer, it can send 640 X 480 digital downlink imagery 100km by employing a two meter antenna (Aerovel, n.d.). High definition (HD) imagery is stored on board for future download (Aerovel, n.d.).While this capability is exceptional, an antenna this large is not compatible with the UTACC CONOPS.

The Aerovel Flexrotor is an incredibly capable vehicle with great potential for the UTACC program in the long term. Should the sensor capability be improved, this is an ideal vehicle to be employed in future iterations of UTACC.

Table 9. Aerovel Flexrotor

Overall Score: 136		
Physical Dimensions: 48	**Performance: 66**	**Sensor: 22**
Length:12	Endurance:30	Modularity: 10
Wingspan / Rotor Diameter: 6	Range: 18	Sensor Options: 10
Weight: 30	Ceiling:18	Number of Sensors:2

5. Latitude Engineering HQ-40

The Latitude Engineering HQ-40 (see Figure 10) is a production vehicle that offers a great deal of promise to the UTACC program, earning an overall score of 150. Along with the other vehicles included in this study by Latitude Engineering, the HQ-40 is a fixed wing vehicle that employs four small electrically powered rotors for VTOL. The electric motors are powered by batteries that can be recharged by on-board generators (Latitude Engineering, n.d.). Once sufficient altitude has been achieved, the rotor system is secured and a 35 cubic centimeter (cc) gas engine provides up to 5 hours of fixed wing flight (Latitude Engineering, n.d.).

Figure 10. Latitude Engineering HQ-40

Source: Latitude Engineering. (n.d.). Retrieved October 17, 2015, from http://latitudeengineering.com/products/hq/

The HQ-40 scored well in all three categories. Table 10 summarizes the aircraft's evaluation scores. With a length of 5.6 feet, a wingspan of 8.3 feet and a maximum takeoff weight of 42 pounds, the vehicle is comparable to the other Group II aircraft. The aircraft's fairly long wingspan is a detriment to the physical score but allows for exceptional performance characteristics as noted previously.

The HQ-40 also scores very well within the sensor category. The aircraft is capable of carrying various types of commercial off the shelf (COTS) sensor turrets which provide excellent flexibility and modularity. With a balanced score among all evaluation criteria the HQ-40 is an excellent candidate for the UTACC program both near and long term.

Table 10. Latitude Engineering HQ-40

Overall Score: 150		
Physical Dimensions: 48	**Performance: 50**	**Sensor: 52**
Length: 12	Endurance: 20	Modularity: 30
Wingspan / Rotor Diameter: 6	Range: 12	Sensor Options: 20
Weight: 30	Ceiling: 18	Number of Sensors: 2

6. Martin UAV V-Bat

Similar to the Aerovel Flexrotor, the Martin UAV V-Bat (see Figure 11) is a tail-sitting VTOL aircraft. Unlike the Flexrotor, the V-Bat employs a ducted fan which provides for VTOL capability as well as thrust for forward flight. This ducted fan configuration also provides a measure of safety over other VTOL aircraft by protecting operators during takeoff and landing. Evaluation scores for the aircraft are summarized in Table 11. The V-Bat earned an overall score of 144 based on strong performance and sensor capability. Due to the aircraft's fixed wing VTOL configuration the V-Bat has an eight-hour endurance. The aircraft scored well in the sensor category based on variety and capacity. While the 9 foot length and 9 foot wingspan are a detriment to the aircraft's physical score, its relative light weight satisfies the metric established for this study.

Figure 11. Martin UAV V-Bat

Source: Martin UAV. (n.d.). Retrieved August 12, 2015, from http://martinuav.com/uav-products/v-bat/

With exceptional endurance and wide array of sensors this is a versatile aircraft that provides another outstanding option for the UTACC program. The V-Bat's large footprint is the primary attribute preventing a higher overall score.

Table 11. Martin UAV V-Bat

Overall Score: 144		
Physical Dimensions: 42	**Performance: 66**	**Sensor: 36**
Length: 6	Endurance: 30	Modularity: 10
Wingspan / Rotor Diameter: 6	Range: 12	Sensor Options: 20
Weight: 30	Ceiling: 18	Number of Sensors:6

7. Scion S-200 Weasel

The Scion S-200 Weasel (see Figure 12) is a rotary wing aircraft employing a fenestron for yaw control and lateral stability. The S-200 performed very well in all categories, particularly in performance and sensor capabilities, earning an overall score of 156. The aircraft has an endurance of approximately four hours and the manufacturer claims it is capable of 10,000 MSL hover out of ground effect (HOGE) with a 50 pound payload (Scion UAS, n.d.). This capability is particularly impressive compared to the other rotary wing aircraft evaluated. While no mention of specific sensors is provided by the manufacturer, the aircraft is capable of carrying a variety of sensors in what are described as payload modules (Scion UAS, n.d.) The performance and sensor scores are exceptional in part due to the large physical dimensions of the aircraft. With a rotor diameter of nearly seven feet and a maximum takeoff weight of 150 pounds, this is the largest aircraft satisfying all evaluation categories. Though impressive, this large size prevents the authors from assigning an even higher overall score to the aircraft despite its capabilities.

Figure 12. Scion S-200 Weasel

Source: Scion UAS S-200 Weasel. (n.d.). Retrieved November 3, 2015, from http://www.scionuas.com/products.html#sa200

According to the manufacturer, a turbine powered variant is in development (S. Mogensen, personal correspondence, 16 November 2015). The greater reliability and efficiency provided by a turbine engine will further improve the performance attributes of this aircraft. Evaluation scores for the S-200 Weasel are summarized in Table 12.

Table 12. Scion S-200 Weasel

Overall Score: 156		
Physical Dimensions: 44	**Performance: 56**	**Sensor: 56**
Length: 12	Endurance: 20	Modularity: 30
Wingspan / Rotor Diameter: 12	Range: 18	Sensor Options: 20
Weight: 20	Ceiling: 18	Number of Sensors: 6

8. Dragonfly Pictures DP-6XT Whisper

The DP-6XT Whisper (see Figure 13) is tandem rotor electrically powered helicopter with an endurance of approximately one hour. It is because of this lesser endurance capability that this aircraft was assigned an overall score of 144. Due to the tandem rotor configuration, the length and wingspan/rotor diameter subcategories for this aircraft are misleading. The overall length is considerable when taking the tandem rotor configuration into account. The evaluated length score of 12 is based upon the fuselage length of 5.9 feet and not the unpublished overall length of both rotor diameters.

Figure 13. Dragonfly Pictures DP-6XT Whisper

Source: Dragonfly Pictures DP-6XT Whisper. (n.d.). Retrieved July 20, 2015, from http://www.dragonflypictures.com/products/unmanned-vehicles/dp-6xt-whisper/

The DP-6XT scores very well in the sensor category due to its modular and flexible sensor capabilities. The flexibility and modularity of the sensor capability come from the aircraft's ability to mount sensors in a gimballed turret and on fuselage-mounted hard points (Dragonfly Pictures, n.d.).

Despite low endurance and a restrictive rotor configuration, the sensor capabilities of the DP-6XT Whisper are impressive as displayed in Table 13. With improved endurance, this aircraft could be a viable solution for future UTACC operations.

Table 13. Dragonfly Pictures DP-6XT Whisper

Overall Score: 144		
Physical Dimensions: 54	**Performance: 34**	**Sensor: 56**
Length: 12	Endurance: 10	Modularity: 30
Wingspan / Rotor Diameter: 12	Range: 6	Sensor Options: 20
Weight: 30	Ceiling: 18	Number of Sensors: 6

9. Latitude Engineering HQ-60

The Latitude Engineering HQ-60 (see Figure 14), similar to the smaller HQ-40, offers an exceptional performance and sensor capability as displayed in Table 14. Employing a rotor system with four electric motors for VTOL and a 70cc engine for sustained fixed wing flight, the HQ-60 has a 15 hour endurance capability. Like the HQ-40, the electric motors are powered by batteries that can be recharged by on board generators (Latitude Engineering, n.d.). The HQ-60 sensor score of 52 is a result of its modularity, variety and quantity of sensors. The aircraft is capable of mounting various turreted COTS EO/IR sensors as well as passive signals intelligence (SIGINT) antenna.

Figure 14. Latitude Engineering HQ-60

Source: Latitude Engineering (n.d.) Retrieved October 17, 2015, from http://latitudeengineering.com/products/hq/

The unique configuration of the HQ-60 provides an excellent platform fulfilling the requirements defined in the UTACC concept. However, the HQ-60 has a wingspan of 12.5 feet and a length of 8.5 feet which give it a footprint less than ideal for the UTACC application.

Table 14. Latitude Engineering HQ-60

Overall Score: 150		
Physical Dimensions: 32	**Performance: 66**	**Sensor: 52**
Length: 6	Endurance: 30	Modularity: 30
Wingspan / Rotor Diameter: 6	Range: 18	Sensor Options: 20
Weight: 20	Ceiling: 18	Number of Sensors: 2

C. CHAPTER CONCLUSION AND AOA FINDINGS

The nine aircraft described in this chapter all satisfy the evaluation criteria established in Chapter III of this study. As mentioned previously, the authors did not consider cost or specific sensors while evaluating these aircraft. In the absence of specific evaluation characteristics any of the vehicles described satisfy the needs of MCWL and UTACC for the RDT&E phase. It should be noted that some options are better suited for only RDT&E while others are suitable for both RDT&E and operational applications. For example, the three Group 1 aircraft; RQ-16, FireFly6, and Hornet Maxi, are only suitable for RDT&E. The following chapter will contain specific recommendations for MCWL in order to select the appropriate aircraft for the UTACC program.

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V. SUMMARY OF RESULTS AND RECOMMENDATIONS FOR FURTHER RESEARCH

This thesis focused on identifying unmanned aerial vehicles (UAV) that best suit the unique needs framed within the UTACC concept. This chapter provides recommendations for aircraft to address both short and long term UTACC requirements and explores both developmental and conceptual designs that may prove to be viable options as they mature. Finally, this chapter will discuss avenues for future research necessary to support UTACC development. In light of UTACC budgetary constraints, the authors first identified aircraft that satisfy the immediate need to further research, development, testing and evaluation (RDT&E). The second recommendation is for aircraft capable of fulfilling the full mission spectrum of the UTACC concept. Aircraft recommended for operational applications of UTACC are also suitable to conduct RDT&E but are cost prohibitive in that capacity.

The authors believe that a hybrid designed aircraft, combining the performance of a fixed wing aircraft with the flexibility of VTOL, is the only viable option for the UTACC program. Through the process of assessment and comparison, the authors concluded that the best performing aircraft were of a fixed wing design. These aircraft have demonstrated longer endurance, longer range and higher ceilings. In general, fixed wing aircraft were also capable of greater payload and sensor options. The study also highlighted the need for aircraft with VTOL capability, noting the UTACC requirement for confined area operations and precision launch and recovery methods.

A. SUMMARY OF RECOMMENDATIONS

Due to the rapid pace of UAV development, a continuous investigation and evaluation of technology, trends and future capabilities will be required by the Marine Corps Warfighting Laboratory (MCWL) to ensure the technological needs of UTACC are appropriately met. To facilitate this the authors have compiled a comprehensive list of vehicles presently applicable to UTACC, and this database will serve as a model for evaluating emerging future aircraft technologies. The author’s summary of results is incorporated in Appendix A. Summary recommendations for RDT&E and Operational deployment follow.

1. Recommendation for RDT&E

The authors recommend the BirdsEyeView Aerobotics FireFly6 for RDT&E due to its low cost, flexible payload, and open source operating system and autopilot. Acquisition costs were not formally evaluated during this study, but the authors did consider fiscal constraints when making their recommendation for an aircraft suitable for near term RDT&E. While only capable of a 2.5-pound payload and limited by a lack of on-board power generation, the aircraft nevertheless presents an excellent balance of cost to capability at approximately $2,000 per aircraft.

An alternative to the BirdsEyeView Aerobotics FireFly6 is the Honeywell RQ-16 T-Hawk. This aircraft is currently in the DOD inventory, dramatically reducing acquisition costs for RDT&E. In addition, the aircraft is familiar to MCWL personnel. As mentioned in Chapter IV, this aircraft has numerous performance limitations which may pose challenges to researchers when incorporating UTACC functionality. Nevertheless, the aircraft can be procured for such minimal cost that the RQ-16 provides significant value to the RDT&E phase of the UTACC program.

2. Recommendation for Operational Implementation

The authors evaluated several vehicles that have the capabilities and attributes necessary for the operational deployment of UTACC. The most impressive of these is the Latitude Engineering HQ-40. The HQ-40 combines the long endurance provided by a fixed wing design with the flexibility of VTOL. In addition to the aircraft's exceptional performance characteristics, the HQ-40 is capable of employing a large array of passive and active sensors which provide significant flexibility to a UTACC unit. The HQ-40 system is estimated to cost approximately $300,000 per unit without sensors.

Other aircraft that satisfy the conceptual requirements of UTACC include the Aerovel Flexrotor, Martin UAV V-Bat, and the Latitude Engineering HQ-60. Each of these vehicles has endurance greater than 8 hours and offers numerous sensor options.

Though these aircraft excel in performance and sensor capability, they are generally larger than the HQ-40 and thus may be less suitable to the UTACC air carrier (AC) concept.

As mentioned earlier, development of unmanned aircraft is moving at a rapid pace. These recommended vehicles presently have the requisite capabilities, but more capable and smaller vehicles may be available in the future that better suit an operational UTACC unit.

B. DEVELOPMENTAL AIRCRAFT NEEDING FUTURE EVALUATION

Unmanned technologies continue to evolve rapidly and are increasingly data-intensive and multi-sensor/multi-mission capable (Secretary of Defense for Acquisition, Technology, and Logistics, 2013). Accordingly, it is critical that MCWL continue to assess current and future unmanned aircraft technologies. Once flight testing is complete and empirical data exists, these developmental aircraft can be included in the database. This will allow database users to continue to assess new technologies against those aircraft already evaluated. The developmental aircraft described in this section offer potential solutions and opportunities to future UTACC applications.

1. Latitude Engineering HQ-20

The HQ-20 (see Figure 15) is a smaller, all-electric variant of the HQ-40 and HQ-60 described in Chapter IV. While it is still in development, the authors believe this aircraft merits further consideration. The HQ-20 is expected to have a length and wingspan of five feet and a maximum takeoff weight of approximately 25 pounds (J. Amer, Latitude Engineering, personal correspondence, 10 December 2015). Coupled with an estimated endurance potential of 2 hours and a sensor capability expected to be similar to the larger HQ-40, this vehicle deserves close consideration as development matures (Latitude Engineering, n.d.). The HQ-20 has ideal physical dimensions and the expected sensor and payload capability promise to fit future UTACC program needs well.

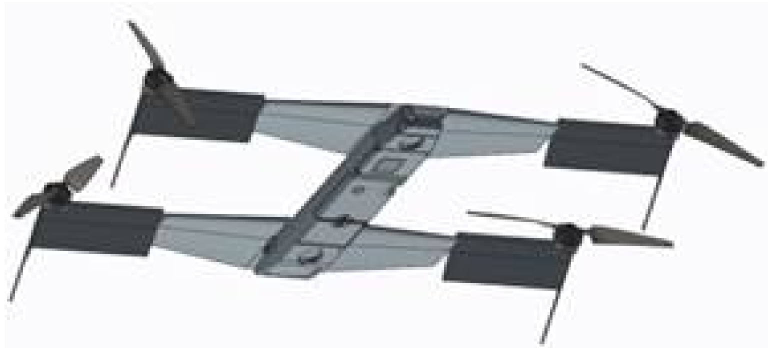
Figure 15. Latitude Engineering HQ-20

Source: Latitude HQ-20. (n.d.). Retrieved October 17, 2015, from https://latitudeengineering.com/products/hq/

2. Lockheed Martin Vector Hawk (Tilt-rotor Variant)

The Lockheed Martin Vector Hawk (see Figure 16) is also a developmental hybrid tilt-rotor aircraft based on an existing production fixed wing vehicle. Estimates provided by the manufacturer suggest that the Vector Hawk would garner an overall score of 120 if evaluated utilizing the criteria described in Chapter III (Lockheed Martin, personal correspondence, 13 November 2015). Due to its small size, the AC could operate multiple Vector Hawks, each employing different sensors, simultaneously. This would mitigate the impact of the vehicles relatively small 0.5 pound payload capability (S. Fortson, Lockheed Martin, personal correspondence, 13 November 2015). The aircraft is estimated to have 1.3 hours of endurance and a maximum ceiling of 17,000 feet MSL which make it suitable for the UTACC program (S. Fortson, Lockheed Martin, personal correspondence, 13 November 2015). Finally, the aircraft's modular sensor suite and expected low acoustic signature enhance the other characteristics inherent in the Vector Hawk tilt-rotor option.

Figure 16. Lockheed Martin Vector Hawk (Tilt-Rotor)



Source: S. Fortson, Lockheed Martin, personal correspondence, 13 November 2015.

It is important to remember that this evaluation is based on manufacturer estimates and this aircraft is not presently available in the near term. If the performance estimates are accurate, the small size and broad sensor capabilities of this aircraft make it an interesting candidate for long term UTACC requirements.

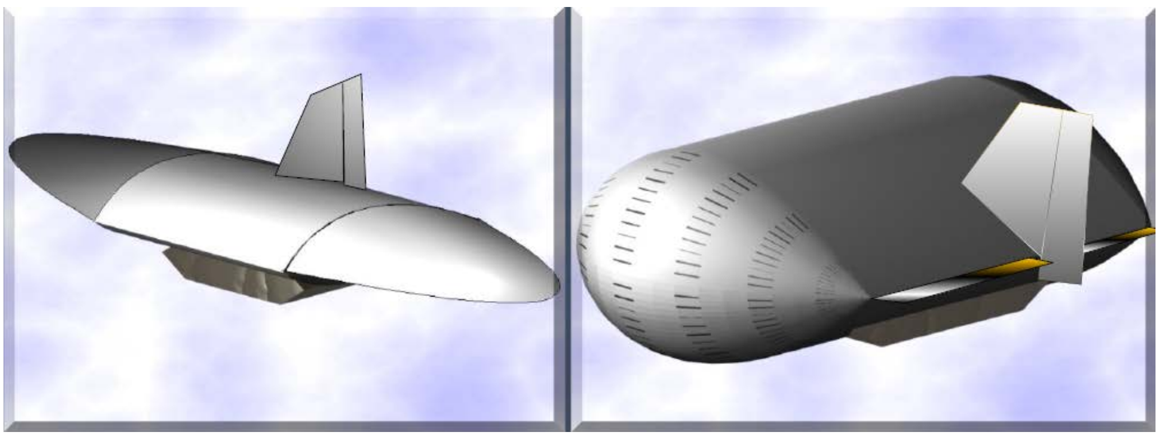
C. CONCEPTUAL AIRCRAFT DESIGNS FOR CONSIDERATION

In addition to developmental advances, UAV research is yielding innovative design concepts. The following section describes some examples of innovative concepts that may be pertinent to UTACC operational applications. These aircraft are far from production ready but it is important to suggest their potential.

1. In-Ovation HyAlta

Lighter-than-air vehicles (LTA) have been employed for the intelligence, surveillance and reconnaissance (ISR) mission for some time. Their application to the modern battlefield has generally been limited to aerostats, primarily as a tethered ISR platform (Assistant Secretary of Defense for Research and Engineering, 2012). In-Ovation Corporation is currently developing the Hybrid Advanced Lighter Than Air (HyAlta) (see Figure 17), an aircraft that combines the benefits of a LTA vehicle with the capability and efficiency of a flying wing (S. Kempshall, In-Ovation, personal correspondence, 30 July 2015). The vehicle itself consists of a sealed wing structure that is capable of quickly changing shape to transform into a traditional LTA balloon form (S. Kempshall, In-Ovation, personal correspondence, 30 July 2015). This transition is dynamic in that the vehicle can conduct flight operations at any number of transformative stages between wing and LTA configuration. Subsequently, the aircraft has a very wide range of flight profile capabilities which gives it the potential to conduct many different missions. With the inherent VTOL characteristics of LTA, the vehicle also has the potential for impressive lift capability. Combining this with the flying wing characteristics of this aircraft's structure likely gives it an extensive range and endurance capability (S. Kempshall, In-Ovation, personal correspondence, 30 July 2015).

Figure 17. In-Ovation HyAlta



Source: S. Kempshall, In-Ovation, personal correspondence, 30 July 2015.

HyAlta is still in early stages of design and development. If it is to be utilized in a future UTACC system several challenges will need to be addressed. These include the management of the compressed gasses necessary for LTA flight and how this management might impact other UTACC components such as the AC. Also, there is a minimum size that LTA will work, and that size, presently, is almost too big for UTACC purposes. If the LTA gas is switched to a mixture of Hydrogen and Helium, then the size could be smaller. Still, this design combination offers great potential mission capability that may fit the UTACC program well.

2. Joby Aviation Lotus

Joby Aviation is developing Lotus (see Figure 18), a unique VTOL aircraft that utilizes an improved rotor system capable of reconfiguration in flight. The vehicle employs a fixed wing frame and melds it with a uniquely designed rotor system that allows for VTOL. After the aircraft lifts off vertically and forward flight is achieved, the wingtip rotors reconfigure. By blending into the wings the rotors become wingtip extensions increasing the wingspan (Stoll, Stilson, Bevirt, & Sinha, 2013). No additional hardware is required, as the same motors that drive the rotor system are utilized in the reconfiguration (Stoll et al., 2013). A tail mounted rotor also pivots forward to provide the sole source of thrust in forward flight (Stoll et al., 2013). This propulsion systems design reduces weight, improves simplicity and has the potential to dramatically improve overall efficiency (Stoll et al., 2013).

Figure 18. Joby Aviation Lotus

Source: Joby Aviation Lotus. (n.d.). Retrieved June 15, 2015, from http://www.jobyaviation.com/lotus/

Though Joby Aviation currently plans a production model Lotus to be larger than what is required by UTACC, there is strong potential that a scaled version would fill the requirements of UTACC well. Joby Aviation's innovative designs make the Lotus a very interesting prospective solution for future application to the UTACC program.

3. Frontline Aerospace V-STAR

Integrated ducted fan technology presents interesting potential avenues for innovation in the realm of UAVs. Frontline Aerospace is developing the VTOL Swift Tactical Aerial Resource (V-STAR) (see Figure 19), an aircraft with impressive potential VTOL, payload and forward flight performance characteristics. Using counter rotating ducted fans for vertical lift and boxed wings with a mechanically linked ducted pusher fan for forward thrust, V-STAR’s flight performance qualities have great potential (Frontline Aerospace, 2009). In addition, a fully modular payload bay can be configured to the desired specifications of the user maximizing the flexibility of missions that the aircraft could perform (Frontline Aerospace, 2009). Three variant V-STARs are in development, and the 1/4 V-STAR model specifically fits the needs of the UTACC program well (Frontline Aerospace, 2009).

Figure 19. Frontline Aerospace V-STAR

Source: Frontline Aerospace V-STAR. (n.d.). Retrieved October 8, 2015, from http://frontlineaerospace.com/wp-content/uploads/2015/11/vstar1-4-datasheet-hr.pdf

Frontline Aerospace has designed an innovative concept that may provide the flight and payload characteristics that are required for the UTACC mission. As with the other conceptual aircraft described in this section, the V-STAR shows potential as an operational solution.

D. RECOMMENDATIONS FOR FUTURE RESEARCH

There are an abundance of research requirements necessary to fully realize the potential of any aircraft associated with the UTACC program. As UTACC requirements evolve and new aircraft are discovered, it is essential that MCWL continue to populate the database developed for this study. Maintaining this database will allow for the continuation of the research conducted for this study and provides a means to evaluate future aircraft options.

Though aircraft are a component of UTACC, it is the act of sensing and sharing information that will govern successful implementation of the system as a whole. Future research into the integration of aircraft subsystems such as sensors, operating systems, autopilot and power sources are critical. The following discussion will briefly examine a few of these suggested areas for future research to complement this study.

1. Sensors

Based on the CONOPS established by Rice et al. (2015) the aircraft employed by UTACC must be capable of all facets of intelligence, surveillance and reconnaissance (ISR). Specific required capabilities include, but are not limited to, area mapping, target recognition, target identification and tracking. Due to the breadth of sensor technology, continued research must be conducted to select an appropriate array of sensors for the UTACC UAV. The aircraft must be able to thoroughly examine an area of interest and share this information with the unit members.

Generally speaking, as sensor capabilities increase, so too does their size, weight and power required. The nature of the UTACC concept necessitates a relatively small aircraft subsequently constraining the size, weight, and power attributes of any sensors and subcomponents placed on-board. Many multi-mode sensors, such as those incorporating forward looking infrared (FLIR), electro-optical/infrared (EO/IR) imagers and light detection and ranging (LIDAR) may be too large for aircraft suitable for UTACC. To mitigate limited payload, consideration should be given to outfitting multiple aircraft with disparate sensors and fusing the data via UTACC.

2. Operating Systems and Autopilots

The logical link between UTACC and the UAV will require robust aircraft operating systems (OS) and autopilot. Outside of the UTACC application, UAVs operate through a logical linkage between a ground station or operator and the aircraft. With respect to UTACC, this linkage is provided by the collaboration and control functions of the system. Therefore, it is critical that the aircraft operating system and autopilot provide a seamless interface with these UTACC functions. The OS subsystem will translate inputs from the overall UTACC system to the aircraft autopilot subsystem commanding flight control inputs directing the aircraft to areas of interest. Upon initiation of ISR, the OS will facilitate the dissemination of the sensor data back to the UTACC interface for interpretation. This critical functionality requires additional research into UTACC UAV subsystem integration.

A final point with respect to the operating and autopilot systems concerns the recovery of the aircraft. While the authors anticipate takeoff functionality of the aircraft to be relatively simple, recovering the aircraft to a moving AC is sure to prove far more challenging, particularly in a denied environment where electromagnetic transmissions are inhibited. Consideration should be given to the ability of the aircraft to autonomously locate the AC and affect a self-recovery employing the aircraft's organic UTACC sensors.

3. Power Source

The limited power sources available to the UTACC unit will affect the concept, development and employment of both ground and air vehicles. As pertaining to this study, sources of power for the aircraft and its associated systems is a subject that must be researched further.

Aircraft operating exclusively on electrical power sources simplifies the logistics requirements. Unfortunately, aircraft with this configuration tend to have lesser performance capabilities. Additional considerations affect the impact that selected sensors have upon the performance of the aircraft. Also of concern is how the AC could generate sufficient power to recharge the aircraft in a tactically acceptable time frame.

Many of the aircraft evaluated in this study provide for on-board power generation through generators driven by the main gas powered engine. This design generally improves performance of the aircraft and sensors but will increase the logistical requirement associated with providing liquid fuel for the aircraft. The type of fuel the aircraft uses must be studied. Ideally, the AC and UAV would employ the same fuel to simplify the logistical requirements. The employment of heavy fuels, such as JP-5 or JP-8, for both AC and UAV could alleviate the need for multiple fuel types.

4. Non-Organic UAV Support

While this thesis focused on an independent small tactical unit defined in the UTACC CONOPS by Rice et al. (2015), the rapid development of UAS and their associated technologies necessitates considering the prospect of employing larger and more capable non-organic UAV assets to support the functionality of UTACC. Employing non-organic assets will certainly pose significant challenges to command and control (C2). As discussed, UTACC is structured around an operationally independent unit capable of executing its mission with integrated UAV assets. If non-organic assets are to be integrated into the UTACC C2 structure in addition to the organic UAV assets envisioned in Rice et al. (2015), research into C2 requirements must be conducted so that they may be clearly defined. Only then can a seamless interaction be reasonably assured.

E. CHAPTER CONCLUSION

The selection of an appropriate UAV to execute the UTACC mission requires more than merely selecting the most capable platform. In addition, continued evaluation of trends and developments in UAV technologies is critical. This study has a provided the attached supplement that can be employed as a tool to achieve this goal. Furthermore, a valid need exists to explore what sensors, logical interfaces and power sources will be required to ensure the aircraft meets the tactical requirements of the UTACC program. The integration of the collaborative and controlling functions is critical to the ensuring the fullest aircraft capability. The depth of discussion contained in this chapter illustrates the challenges of developing an appropriate fully mission capable UAV system for the UTACC program.

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APPENDIX A. SUMMARY OF RESULTS

Vehicle	Scion UAS SA-200 Weasel	Latitude HQ-40	Latitude HQ-60	DPI DP-6XT Whisper	Martin UAV V-Bat	Aerovel Flexrotor	Honeywell International RQ-16 T-Hawk	Adaptive Flight Hornet Maxi UAS	BirdsEyeView Aerobotics FireFLY6
Endurance Weighted Score	20	20	30	10	30	30	10	10	10
Range Weighted Score	18	12	18	6	12	18	6	6	6
Ceiling Weighted Score	18	18	18	18	18	18	12	18	12
Performance Overall	**56**	**50**	**66**	**34**	**66**	**66**	**28**	**34**	**28**
Length Weighted Score	12	12	6	12	6	12	12	12	12
Wingspan/Rotor Diameter Weighted Score	12	6	6	12	6	6	12	12	12
Weight Weighted Score	20	30	20	30	30	30	30	30	30
Physical Overall	**44**	**48**	**32**	**54**	**42**	**48**	**54**	**54**	**54**
Modularity Weighted Score	30	30	30	30	10	10	30	10	10
Sensor Options Weighted Score	20	20	20	20	20	10	10	20	10
Number of Sensors Weighted Score	6	2	2	6	6	2	2	2	6
Sensor Overall	**56**	**52**	**52**	**56**	**36**	**22**	**42**	**32**	**26**
Combined Overall	**156**	**150**	**150**	**144**	**144**	**136**	**124**	**120**	**108**

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APPENDIX B. UAV SOURCE WEBSITES

The websites contained in this appendix constitute the source data for all aircraft and their respective manufacturers evaluated during this study. The aircraft column contains the manufacturer and aircraft model names. The source website column contains the specific uniform resource locator (URL) for the associated aircraft.

AIRCRAFT	SOURCE WEBSITE
Acuity Technologies AT-10	http://www.acuitytx.com/pdf/Acuity%20Technologies%20AT-10%20Brief.pdf
Adaptive Flight Hornet Mini	http://www.adaptiveflight.com/products/hornet-mini/hornet-mini-introduction/hornet-mini-specs/
Aerovel Flexrotor	http://aerovelco.com/flexrotor/
Aerovironment Qube	http://www.avinc.com/uas/small_uas/qube/
Aerovironment Shrike	http://www.avinc.com/uas/small_uas/shrike/
Aerovironment Puma	http://www.avinc.com/uas/small_uas/puma/
Aerovironment Raven	http://www.avinc.com/uas/small_uas/raven/
Aerovironment Wasp AE	http://www.avinc.com/uas/small_uas/waspAE/
Aerovironment Switchblade	http://www.avinc.com/uas/small_uas/switchblade/
Allied Drones AW1	http://allieddrones.com/portfolio-item/aw1/
American Aerospace Advisors, Inc. RS-16	https://s3.amazonaws.com/americanaerospace/American+Aerospace+Systems+Tearsheet.pdf
American Aerospace Advisors, Inc. RS-20	https://s3.amazonaws.com/americanaerospace/American+Aerospace+Systems+Tearsheet.pdf
Arcturus UAV Jump 15	http://arcturus-uav.com/product/jump-15
Arcturus UAV Jump 20	http://arcturus-uav.com/product/jump-20
Aurora Flight Sciences GoldenEye 80	http://skate.aero/Development/GoldenEye_80.aspx

AIRCRAFT	SOURCE WEBSITE
Aurora Flight Sciences Skate	http://skate.aero/Products/Skate.aspx
BirdsEyeView Aerobotics FireFly6	http://www.birdseyeview.aero/products/firefly6
BrockTek Havoc	http://www.brocktekus.com/#!services/cea9
BrockTek Shark	http://www.brocktekus.com/#!shark/cag8
BrockTek AV-8R	http://www.brocktekus.com/#!av8r/c24c8
BrockTek BT-20 Eel	http://www.brocktekus.com/#!eel/ctpp
BrockTek Spear	http://www.brocktekus.com/#!spear/c14u2
Dara Aviation D-1	http://www.daraaviation.com/Downloads/D1-info.pdf
Dragonfly Pictures DP-12 Rhino	http://www.dragonflypictures.com/products/unmanned-vehicles/dp-12-rhino/
Dragonfly Pictures DP-6XT Whisper	http://www.dragonflypictures.com/products/unmanned-vehicles/dp-6xt-whisper/
Dragonfly Pictures DP-5X Wasp	http://www.dragonflypictures.com/products/unmanned-vehicles/dp-5x-wasp/
Falcon UAV Falcon	http://www.falconunmanned.com/falcon-falcon/
Frontline Aerospace V-STAR	http://frontlineaerospace.com/wp-content/uploads/2015/11/vstar1-4-datasheet-hr.pdf
Guided Systems Technologies SiCX-10E	http://guidedsys.com/all_product/sic-x-10e/
Guided Systems Technologies SiCX-75	http://guidedsys.com/all_product/sicx-7/
Honeywell International RQ-16 T-Hawk	http://www51.honeywell.com/aero/common/documents/myaerospacecatalog-documents/Defense_Brochures/T-Hawk_MAV.pdf
Insitu Integrator	http://www.insitu.com/systems/integrator
Insitu Scan Eagle	http://www.insitu.com/systems/scaneagle
Joby Aviation Lotus	http://www.jobyaviation.com/lotus/

AIRCRAFT	SOURCE WEBSITE
Krossblade Aerospace Skyprowler	http://www.krossblade.com/#skyprowler-section
L-3 Unmanned Systems APEX	http://www2.l-3com.com/uas/products/r_apex.htm
L-3 Unmanned Systems (Geneva Aerospace) Cutlass	http://www2.l-3com.com/uas/products/r_cutlass.htm
Latitude HQ-20	https://latitudeengineering.com/products/hq/
Latitude HQ-40	https://latitudeengineering.com/products/hq/
Latitude HQ-60	https://latitudeengineering.com/products/hq/
Lockheed Martin Vector Hawk	http://www.lockheedmartin.com/us/news/press-releases/2014/may/140513-mst-lm-introduces-latest-addition-to-suas-family.html
Lockheed Martin INDAGO	http://www.lockheedmartin.com/us/products/procerus/indago-uas.html
Lockheed Martin Desert Hawk	http://www.lockheedmartin.com/us/products/desert-hawk.html
Lockheed Martin Stalker	http://www.lockheedmartin.com/us/products/stalker-uas.html
Lockheed Martin Missiles and Fire Control Terminator	https://www.flightglobal.com/news/articles/lockheed-displays-new-look-terminator-uav-417776/
Lockheed Martin Unmanned Integrated Systems Fury	http://www.lockheedmartin.com/us/products/fury.html
Martin UAV Super Bat DA-50	http://martinuav.com/products-super-bat-da-50/
Martin UAV V-Bat	http://martinuav.com/products-v-bat/
Martin UAV S-Bat	http://martinuav.com/products-s-bat/
Martin UAV Bat-4	http://martinuav.com/products-bat-4/
Mission Technology Systems Buster ER	http://missiontechsys.com/assets/BUSTER%20FLYER.pdf
Mission Technology Systems Blacklight	http://missiontechsys.com/assets/BLACKLIGHT%20FLYER.pdf

AIRCRAFT	SOURCE WEBSITE
Mission Technology Systems Buster	http://missiontechsys.com/assets/BUSTER%20FLYER.pdf
Moller International Aerobot	http://www.moller.com/aerobot.html
Northrop Grumman R-Bat	http://www.northropgrumman.com/Capabilities/RBat/Pages/default.aspx
Northrop Grumman Bat	http://www.northropgrumman.com/Capabilities/BATUAS/Pages/default.aspx
Prioria Robotics Maveric	http://www.prioria.com/maveric/
Raytheon Silverfox	http://www.raytheon.com/capabilities/products/silverfox/
Raytheon Manta	http://www.raytheon.com/capabilities/products/manta/
Raytheon Coyote	http://www.raytheon.com/capabilities/products/coyote/
Scion UAS S-200 Weasel	http://www.scionuas.com/products.html#sa200
Scion UAS S-400 Jakal	http://www.scionuas.com/products.html#sa400
Silent Falcon UAS Technologies Silent Falcon	http://www.silentfalconuas.com/Silent-Falcon.html
Swift Engineering X-Blade	http://www.swiftengineering.com/x-blade
Textron Systems Unmanned Systems Shadow 200	http://www.textronsystems.com/products/unmanned/shadow
Textron Systems Unmanned Systems Shadow M2	http://www.textronsystems.com/products/unmanned/shadow_m2
Textron Systems Unmanned Systems Aerosonde	http://www.textronsystems.com/products/unmanned/aerosonde
UAV Factory Penguin B	http://www.uavfactory.com/page/technical-data
UAV Factory Penguin BE	http://www.uavfactory.com/page/technical-data
UAV Factory Penguin C	http://www.uavfactory.com/page/technical-data
UAV Solutions Phoenix 60	http://uav-solutions.com/wp-content/uploads/2015/04/Multi-Rotor-Brochure.pdf
UAV Solutions Phoenix 60LE	http://uav-solutions.com/wp-content/uploads/2015/04/Multi-Rotor-Brochure.pdf

AIRCRAFT	SOURCE WEBSITE
UAV Solutions MAAX	http://www.unmannedsystemstechnology.com/wp-content/uploads/2013/05/UAV-Solutions-MAAX.pdf
UAV Solutions Intruder	http://uav-solutions.com/intruder-unmanned-aircraft-system/
UAV Solutions Sidewinder	http://uav-solutions.com/sidewinder-unmanned-aircraft-system/
UAV Solutions Talon 120	http://uav-solutions.com/wp-content/uploads/2015/04/Fixed-Wing-Brochure.pdf
UAV Solutions Talon 240	http://uav-solutions.com/wp-content/uploads/2015/04/Fixed-Wing-Brochure.pdf
Vanguard Defense Industries Shadow Hawk	http://media.wix.com/ugd/709bcc_afcf73d27be44c7e82d0029f04743c11.pdf

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SUPPLEMENTAL

The complete Unmanned Aerial Vehicle (UAV) Database as an Excel spreadsheet can be obtained by contacting the Naval Postgraduate School's Dudley Knox Library.

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LIST OF REFERENCES

Adaptive Flight Hornet Maxi. (n.d.). Retrieved July 6, 2015, from http://www.adaptiveflight.com/products/maxi/hornet-maxi-introduction/hornet-maxi-specs/

Aerovel Flexrotor. (n.d.). Retrieved July 12, 2015, from http://aerovelco.com/flexrotor/

Assistant Secretary of Defense for Research and Engineering. (2012). *Summary report of DOD funded lighter-than-air vehicles*. Retrieved from http://www.dtic.mil/dtic/tr/fulltext/u2/a568211.pdf

BirdsEyeView Aerobotics FireFly6. (n.d.). Retrieved July 12, 2015, from http://www.birdseyeview.aero/products/firefly6

Bruemmer, D., Ferlis, R., Huang, H., Novak, B., Schultz, A., & Smith, R. (2004). *Autonomy Levels for Unmanned Systems (ALFUS) framework volume I: Terminology* (NIST Special Publication 1011). Gaithersburg, MD: National Institute of Standards and Technology.

Brungardt, J. (2012). *Introduction to Unmanned Aircraft Systems*. R. K. Barnhart, S. B. Hottman, D. M. Marshall, & E. Shappee (eds.), Boca Raton, FL: CRC Press. Retrieved from http://www.crcnetbase.com.libproxy.nps.edu/isbn/9781439835203

Brown, B. (2010). *Introduction to defense acquisition management* (10th ed.). Fort Belvoir, VA: Defense Acquisition University Press.

Chen, J. Y. C., & Barnes, M. J. (2014). Human–Agent teaming for multirobot control: A review of human factors issues. *IEEE Transactions on Human-Machine Systems, 44*(1), 13–29.

Defense Acquisition University. (2013). Defense Acquisition Guidebook. Retrieved from https://acc.dau.mil/docs/dag_pdf/dag_complete.pdf

Department of Defense. (2003). *Design Criteria Standard: Human engineering* (MIL-STD-1472F). Washington, DC: Author. Retrieved from http://www.dtic.mil/dtic/tr/fulltext/u2/a550252.pdf

Dragonfly Pictures DP-6XT Whisper. (n.d.). Retrieved July 20, 2015, from http://www.dragonflypictures.com/products/unmanned-vehicles/dp-6xt-whisper/

Fahlstrom, P. G., & Gleason T. J. (2012). *Introduction to UAV Systems.* West Sussex, UK: John Wiley & Sons, Ltd.

Frontline Aerospace V-STAR. (n.d.). Retrieved October 8, 2015, from http://frontlineaerospace.com/wp-content/uploads/2015/11/vstar1-4-datasheet-hr.pdf

Glotzbach, T. (2004). Adaptive autonomy: A suggestion for the definition of the notation 'autonomy' in mobile robotics. *Proceedings of the 2004 IEEE International Conference on Control Applications*, *2*, 922–927. doi: 10.1109/cca.2004.1387487

Honeywell International RQ-16 T-Hawk. (n.d.). Retrieved August 21, 2015, from http://www51.honeywell.com/aero/common/documents/myaerospacecatalog-documents/Defense_Brochures/T-Hawk_MAV.pdf

Jane's All the World Aircraft: Unmanned. Retrieved from https://janes.ihs.com/CustomPages/Janes/ReferenceHome.aspx

Jarnot, C. (2012) *Introduction to Unmanned Aircraft Systems* R. K . Barnhart, S. B. Hottman, D. M. Marshall, and E. Shappee, (eds). Boca Raton, FL: CRC Press. Retrieved from http://www.crcnetbase.com.libproxy.nps.edu/isbn/9781439835203

Joby Aviation Lotus. (n.d.). Retrieved June 15, 2015, from http://www.jobyaviation.com/lotus/

Joint Chiefs of Staff. (2014). *Command and control of joint air operations* (Joint Publication 3-30). Washington, DC: Retrieved from http://www.dtic.mil/doctrine/new_pubs/jp3_30.pdf

Kemp, I. (Ed.). (2015). *Unmanned vehicles handbook.* Derbyshire, UK: Shephard.

Kendall, F. (2014). *Terms of Reference – Defense Science Board 2015 Summer Study on Autonomy* [Memorandum]. Washington, DC: Department of Defense. Retrieved from http://www.acq.osd.mil/dsb/tors/TOR-2014-11-17-Summer_Study_2015_on_Autonomy.pdf

Latitude HQ-20. (n.d.). Retrieved October 17, 2015, from https://latitudeengineering.com/products/hq/

Latitude HQ-40. (n.d.). Retrieved October 17, 2015, from https://latitudeengineering.com/products/hq/

Latitude HQ-60. (n.d.). Retrieved October 17, 2015, from https://latitudeengineering.com/products/hq/

Lockheed Martin Vector Hawk. (n.d.). Retrieved October, 2015, from http://www.lockheedmartin.com/us/news/press-releases/2014/may/140513-mst-lm-introduces-latest-addition-to-suas-family.html

Martin UAV V-Bat. (n.d.). Retrieved August 12, 2015, from http://martinuav.com/products-v-bat/

Office of Aerospace Studies. (2013). *Analysis of alternatives (AoA) handbook: A practical guide to the analysis of alternatives*. Kirtland, AFB. Retrieved from http://afacpo.com/AQDocs/OASAoAHandbook10June2013.pdf

Rice, T. M., Keim, E.A., & Chhabra, T. (2015). Unmanned Tactical Autonomous Control and Collaboration Concept of Operations (Master's Thesis). Retrieved from Calhoun http://calhoun.nps.edu/bitstream/handle/10945/47319/15Sep_Rice_Keim_Chhabra_Needs_Supplemental.pdf?sequence=1&isAllowed=y

Scion UAS S-200 Weasel. (n.d.). Retrieved November 3, 2015, from http://www.scionuas.com/products.html#sa200

Secretary of Defense for Acquisition, Technology, and Logistics. (2007). *The Defense Acquisition System* (DODINST 5000.01). Washington, DC: Government Printing Office.

Secretary of Defense for Acquisition, Technology, and Logistics. (2012). *The role of autonomy in DOD Systems*. Washington, DC: Government Printing Office.

Secretary of Defense for Acquisition, Technology, and Logistics. (2013). *The unmanned systems integrated roadmap FY 2013–2038*. Washington, DC. Retrieved from http://archive.defense.gov/pubs/DOD-USRM-2013.pdf

Secretary of Defense for Acquisition, Technology, and Logistics. (2015). *Operation of the Defense Acquisition System* (DODINST 5002.02). Washington, DC: Government Printing Office.

Shaker, S, & Wise, A. (1988). *War Without Men: Robots on the Future Battlefield.* Washington, DC: Pergamon-Brassey.

Siegwart, R., Nourbakhsh, I., and Scaramuzza, D. (2011). *Introduction to autonomous mobile robots.* Boston, MA: MIT Press.

Statement of work (SOW): Concept of operations for unmanned tactical autonomous control and collaboration project. (2014). Naval Postgraduate School and Marine Corps Warfighting Laboratory, unpublished manuscript.

Stoll, A. M., Stilson, E. V., Bevirt, J., & Sinha, P. (2013). *A Multifunctional Rotor Concept for Quiet and Efficient VTOL Aircraft*. Paper presented at the 14th AIAA Aviation Technology, Interaction, and Operations Conference, Los Angeles, CA. Retrieved from http://www.jobyaviation.com/MultifunctionalRotorConcept%28AIAA%29.pdf

United States Geological Survey. (n.d.) RQ-16A T-Hawk poster. Retrieved February 16, 2016, from: http://uas.usgs.gov/pdf/THawk/THawk_poster_24x32.pdf

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