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THESIS

CLOSING THE GAP BETWEEN RESEARCH AND FIELD APPLICATIONS FOR MULTI-UAV COOPERATIVE MISSIONS

by

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September 2013

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The ability to fly multiple unmanned aerial vehicles (UAVs) in collaboration has the potential to expand the scope of feasible UAV missions and could become the backbone of future UAV missions. However, despite having garnered significant research interest, there is no indication that systems supporting collaborative operation of multiple UAVs are close to achieving field deployment. The challenge of successfully deploying a quality system is inherently complex, and systems engineering offers an approach to handle the complexities. Effective application of systems engineering requires both knowledge breadth and depth. This thesis presents the results of a consolidation of information intended to support the conduct of systems engineering activities; and describes an experiment to ascertain the sensitivities of some key operational parameters, e.g., acquisition, pointing, and tracking. The experiment was conducted using Automatic Dependent Surveillance–Broadcast (ADS-B) and visual tracking equipment employing state-of-the-art technology to understand the operating challenges and requirements of using this equipment to provide situational awareness for a UAV pilot.

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CLOSING THE GAP BETWEEN RESEARCH AND FIELD APPLICATIONS FOR MULTI-UAV COOPERATIVE MISSIONS

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ABSTRACT

The ability to fly multiple unmanned aerial vehicles (UAVs) in collaboration has the potential to expand the scope of feasible UAV missions and could become the backbone of future UAV missions. However, despite having garnered significant research interest, there is no indication that systems supporting collaborative operation of multiple UAVs are close to achieving field deployment. The challenge of successfully deploying a quality system is inherently complex, and systems engineering offers an approach to handle the complexities. Effective application of systems engineering requires both knowledge breadth and depth. This thesis presents the results of a consolidation of information intended to support the conduct of systems engineering activities; and describes an experiment to ascertain the sensitivities of some key operational parameters, e.g., acquisition, pointing, and tracking. The experiment was conducted using Automatic Dependent Surveillance–Broadcast (ADS-B) and visual tracking equipment employing state-of-the-art technology to understand the operating challenges and requirements of using this equipment to provide situational awareness for a UAV pilot.

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LIST OF ACRONYMS AND ABBREVIATIONS

ABCS	Army Battle Command System
ABSAA	Airborne Sense and Avoid
ADS-B	Automatic Dependent Surveillance – Broadcast
AGS	Alliance Ground Surveillance System
AO	Area of Operation
BACN	Battlefield Airborne Communications Node
BLOS	Beyond-line-of-sight
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance
CBBA	Consensus Based Bundle Algorithm
CEC	Cooperative Engagement Capability
CONOPs	Concept of Operations
COTS	Commercial-off-the-shelf
CR	Cognitive Radios
DDG	Arleigh Burke-Class Aegis Guided-Missile Destroyer
DoD	Department of Defense
DRR	Due Regard Radar
DSA	Dynamic Spectrum Access
ELINT	Electronic Intelligence
EO/IR	Electro-Optics/Infra-Red
FAA	Federal Aviation Administration
FCS	Future Combat System
FMV	Full Motion Video
FOV	Field of View
GA-ASI	General Atomics Aeronautical Systems, Inc.
GBSAA	Ground-based Sense and Avoid
GCS	Ground Control Station
GDT	Ground Data Terminal
GIG	Global Information Grid
GPS	Global Positioning System

GUI	Graphical User Interface
HALE	High Altitude Long Endurance
HMI	Human Machine Interface
IADS	Integrated Air Defense Systems
ICD	Initial Capabilities Document
IED	Improvised Explosive Device
IEEE	Institute of Electrical and Electronics Engineers
IMU	Inertial Measurement Units
INCOSE	International Council on Systems Engineering
ISR	Intelligence Surveillance and Reconnaissance
ISTAR	Intelligence, Surveillance, Target Acquisition and Reconnaissance
JTRS	Joint Tactical Radio System
LOI	Level of Interoperability
LOS	Line of Sight
MALE	Medium Altitude Long Endurance
MANA	Map Aware Non-uniform Automata
MISM	Motion Imagery Systems Matrix
MUM	Manned Unmanned Teaming
NAS	National Airspace System
NATO	North Atlantic Treaty Organization
NCW	Network Centric Warfare
NPS	Naval Postgraduate School
NUS	National University of Singapore
OA	Open Architecture
OCA	Offensive Counter Air
OEF	Operation Enduring Freedom
OIF	Operation Iraqi Freedom
OSD	Office of Secretary of Defense
PED	Processing, Exploitation, and Dissemination
RDE	Rheinmetall Defense Electronics
RPA	Remotely Piloted Aircraft
SAA	Sense and Avoid

SAR	Synthetic Aperture Radar
SATCOM	Satellite Communication
SIGINT	Signals Intelligence
SLAM	Simultaneous Localization and Mapping
SOA	Service-oriented Architecture
TDSI	Temasek Defence Science Institute
UAS	Unmanned Aircraft Systems
UAV	Unmanned Aerial Vehicle
UI	User Interface
VO	Visual Odometry
WIN-T	Warfighter Information Network–Tactical
ZCA	Zero Conflict Airspace

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EXECUTIVE SUMMARY

The use of unmanned aerial vehicle[1] (UAV) for military, border security, coastal security, and disaster relief operations is increasing in the United States and other countries. In the past ten years, a number of reports have been released by the United States military and other United States government agencies that document the success of Unmanned Aircraft Systems (UAS), challenges and the vision for the future. The ability to fly multiple UAVs[2] (multi-UAVs) in collaboration has the potential to expand the scope of feasible UAV missions and could become the backbone of future UAV missions. However, despite having garnered significant research interest, the literature reviewed did not present conclusive evidence that systems employing a multi-UAV collaborative approach for a common mission are close to achieving field deployment, and there are reasons to believe certain activities are still needed to complete the transition from research interest to deployed systems. The literature review indicates that there are design concepts, concepts of operations (based on a minimal set of requirements, i.e., Navy), advanced research and development work on critical items, early layout of a technology roadmap, and a development plan with risk factors. All of these are inferred through systems engineering analysis based on [1], [2] and [3].

The challenge of successfully deploying a quality system is inherently complex. A system or a system of systems designed for cooperative/collaborative applications is likely to be complex. The system requires interoperability between systems. In addition, the United States Air Force UAS Flight Plan mentioned that future UAS should be multi-

[1] Many terms have been used to refer to systems involving unmanned aircraft (e.g., UAV, RPA and UAS). The terms UAV and UAS appear frequently in this thesis. In the context of this thesis, the term UAV is used loosely to refer to the unmanned aircraft. The UAV, together with other ground elements required to operate the UAV, is collectively termed the Unmanned Aerial System (UAS).

A majority of the time, this thesis makes no clear distinction when using the term UAV and UAS. In the implementation level of details, functionalities can be implemented either on board the aircraft or on the ground station. The choice of where to implement the respective functions is important when making an assessment of the design. However, this level of detail is not required for the context of this thesis.

[2] The term multi-UAVs is used to refer to a concept or design involving the use of multiple UAVs. The use of the term does not imply the disregard of the ground and other components that form the complete system but is used to refer to the general concept, without dwelling on the details of the exact design of the complete system.

mission, all weather, net-centric, and modular, and should have an open architecture and employ leveraging of appropriate levels of autonomy. A similar view is echoed by the United States Army UAS roadmap. Collectively, the requirement for collaborative operations and multi-mission UAV platforms pose a design challenge that warrants elaborate study into needs, requirements, limitation and constraints, coupling and cohesion, and emergent behavior. Systems engineering offers a means to manage the complexity. However, the breadth and depth of a practitioner's knowledge limits how "holistic" a view he could adopt when performing tasks, potentially affecting the quality success of the system. In addition, the process of moving from an idea to a deployed system would involve numerous studies, which not only requires domain knowledge, but also requires time and other resources to conduct the studies. This thesis attempts to consolidate information, such as potential areas of application that have generated interest, technological enablers and associated research, and interpretation of the status of the technology with regard to deploying multi-UAVs cooperative systems. The intention is to lay the groundwork for future conduct of gap analysis and other systems engineering activities. An experiment was also conducted in a chosen technology area, situational awareness, as part of this thesis. The experiment was conducted using Automatic Dependent Surveillance – Broadcast (ADS-B) and visual tracking equipment employing state-of-the-art technology to understand the operating challenges and requirements of using this equipment to provide situational awareness for the UAV pilot.

In Concept of Operations (CONOPs) for multi-UAVs operations that are published by military services or strongly supported through the conduct of a holistic assessment, the areas of applications that had generated a significant amount of research interest and discussion were narrowed to Urban Operations, Communications Support, Collaborative Sensing, Swarm (Wide area search, EW, Offensive and Defensive) and loyal wingman applications. The factors driving the interest for these applications (to address user needs) were the need for timely and updated intelligence regarding a dynamic urban environment, need for affordable connectivity with sufficient bandwidth and a desire to capitalize on opportunities made feasible with small UAS. In addition, the desire to do more with unmanned systems and the a need to reduce manpower and logistics requirement associated with operating UASs also play a part in attracting operational and research interest. The primary technical areas, such as collision avoidance, Global Positioning System (GPS) denied navigation, autonomy, communication network, interoperability and power, were discussed in depth, including some of the algorithms being researched for the respective applications.

There are a few remaining technical and political obstacles that need to be overcome for multiple UAV operations. The key technological elements include collision avoidance, GPS denied navigation, autonomy, communication network, interoperability and power. The political issues span the gamut of questions on the legality of use and regulations not keeping pace with UAS developments to pressure from human rights organizations and political leaders.

The ADS-B, part of Federal Aviation Administration (FAA) larger airspace modernization efforts and an element with a significant amount of mention in discussion regarding integration of UAS into National Airspace System (NAS), seems to offer much promise as a platform to answer many questions regarding the requirements to safely operate UAS with other manned aviation elements. Successful integration of UAVs into commercial airspace will likely provide a design reference and serve as a platform that provides more opportunities to obtain relevant data for study. In addition, the success could help boost confidence and shape general acceptance of operating UAVs with other aircraft (including other UAVs) in no-segregated airspace [4]. The tasks for full implementation of ADS-B and other measures are planned to be completed over the years to follow. Conditions are probably still not right for an ambitious attempt at elaborate designs to handle multiple high risk requirements, a potential lesson learned from the Future Combat System (FCS) development. FCS was the United States Army's major research, development and acquisition program, consisting of 14 manned and unmanned systems tied together by an extensive communications and information network [5]. FCS, a high-risk venture that was eventually halted in 2009 [5], was criticized in a GAO report for reasons such as critical technology demonstrated being well short of a program halfway through its development schedule and budget [6]. However, there are numerous research papers in various technical domains with relevance to multi-UAV applications that have been published [7]–[13] suggesting there may be sufficient maturity across domains to begin assessment studies or conduct of experiments which take into consideration multi-dimensional constraints and to begin a progressive evolution towards the desired vision for multi-UAV applications.

Several writers who follow military news and write about military applications, such as [3] and [14], discuss interest (for example, the U.S. Navy interest in Unmanned Carrier-launched airborne surveillance and strike) and capabilities for UAS, while there is an absence of published CONOPs from any military service in the public domain. A CONOPS is a description of how users will employ a product or service. This description is normally both qualitative and quantitative. CONOPS (or ConOps) are always included in any government request for information (according to a private communication with Professor Gary Langford, NPS). Validation of the information that comprises a CONOPS is merely to point out that the information is appropriate and fit for its stated use. The CONOPS is used to guide validation of the user's needs and to help guide the validation planning, testing, and eventually the validation of the system. The other key obstacles to full disclosure on military interest in UAS are the human-related factors, regulations and legal restrictions. The "UAV revolution," like any form of change, must overcome the tendency of humans to resist change. Although reports from military services [1] and other government agencies [15] and [16] have shown the operational value of UAVs, full scale adoption remains thwarted by the technical and political obstacles mentioned. Legislation, regulations and standards need to be considered and revised as along with the concerns of the regulatory and legal authorities.

In the conduct of the experiment for this thesis, the author flew as a passenger on board a general aviation aircraft and attempted to visually spot and track other aircraft while being assisted with ADS-B data. In addition, the PerceptiVU and SkyIMD set-ups were used to attempt to manually steer the respective camera sensor onto aircraft of interest and activate the track function of the respective set-ups to track the aircraft. The PerceptiVU and SkyIMD set-ups were assembled on the roof of Spanagel Hall in NPS. The Flightradar24 application was also used to provide better awareness of the aircraft in the vicinity and to provide altitude and airspeed data of the aircraft being tracked. In the conduct of both tasks, the author had significant advantages over the case where a UAV pilot situated remotely in a control station is trying to maintain awareness of the air traffic vicinity while aided only by a visual sensor. Nevertheless, both tasks were found to offer their share of challenges. Some lessons were learned from the experience. First, a visual sensor set-up alone is probably insufficient. Second, the mechanism requiring the pilot to perform steering and execute tracking is probably not feasible. Third, consideration for the position of the visual sensor is important. Lastly, design considerations to improve presentation of information and the mechanism to operate and control the equipment are required.

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I. INTRODUCTION

A. BACKGROUND

The use of unmanned aerial vehicles (UAVs) for military, border security, coastal security, and disaster relief operations is common in the United States and other countries. Over the years, various UAVs have been designed and produced by the industry to meet a wide spectrum of missions. Well known UAV platforms employed by the United States military include the Raven (RQ-11B), Shadow 200 (RQ-7) and Predator (RQ-1/MQ-1) [17]. Globally, examples of platforms operated by the United Kingdom's military include the Hermes 450 and T-Hawk. The North Atlantic Treaty Organization (NATO) is acquiring Global Hawk (RQ-4) as part of their Alliance Ground Surveillance System (AGS). Israel, India and Turkey operate the Heron UAV [18]. The Singapore Armed Forces have also invested in UAV related projects. The Heron 1 UAV is the new platform deployed and operated by that nation [19].

UAVs have been used with considerable success in recent deployments in Iraq and Afghanistan.

> Experiences in Operation Enduring Freedom (OEF) and Operation Iraqi Freedom (OIF) prove that UAS significantly augment mission accomplishment by reducing a Soldier's workload and their exposure to direct enemy contact. The UAS serve as unique tools for the commander, which broaden battlefield situational awareness and the ability to see, target, and destroy the enemy by providing actionable intelligence to the lowest tactical level. [1]

In the past ten years, a number of reports have been released by the United States military and other United States government agencies that document the success of Unmanned Aircraft Systems (UAS), challenges and the vision for the future. Examples of roadmaps are “”*U.S. Army Roadmap for Unmanned Aircraft Systems 2010*–2035: *Eyes of the Army* [1] and *United States Air Force Unmanned Aircraft Systems Flight Plan 2009–2047* [20]. Examples of other reports include *Unmanned Aircraft Systems–Improved Planning and Acquisition Strategies Can Help Address Operational Challenges* and

Unmanned Aircraft Systems—DoD Needs to More Effectively Promote Interoperability and Improve Performance Assessments [21].

In the context of the United States Army, various types of UAV platforms have been used support activities at each level of Army echelons. At the Battalion-level or lower, UAVs capable of close range (less than 25km), short duration (1 to 2 hours) missions are integrated as an organic asset to support tactical operations [1]. Brigade-level operates UAVs capable of medium range (less than 125km), medium duration (5 to 10 hours) missions that integrate with ground forces and other aviation assets [1]. Division-level and higher operates UAVs capable of extended range (200km or more), long duration (16 hours or more) missions that provide direct support or general support at the tactical or operational level [1]. Primary application of the UAS in the military context is within the area of Reconnaissance and Surveillance, and improving situation awareness of the battlespace. Examples of secondary roles include providing security for troop maneuvers, and administration of attack and target designation. Increasingly, the UAS is viewed as a component within a larger network of System of Systems in a Network Centric Warfare context, an integrated component for Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance (C4ISR).

The ability to fly multiple UAVs in collaboration has the potential to expand the scope of feasible UAV missions and could become the backbone of future UAV missions. Researchers have noticed the potential and various papers have been written and published presenting results of studies in related areas. At the Naval Postgraduate School (NPS), Gerard Leng (NUS) and Oleg Yakimenko co-wrote "Situational Awareness in Urban Areas" to describe the first joint project between the National University of Singapore (NUS) and NPS, sponsored by Temasek Defence Science Institute (TDSI) [22]. Levi Jones and Chua Chee Nam completed their theses in related areas titled, "Coordination and Control for Multi-Quadrotor UAV Missions" [12] and "Integration of Multiple UAVs for Collaborative ISR[3] Missions in an Urban Environment" [23], respectively during their period of studies at NPS. Examples outside of NPS include

[3] Intelligence, Surveillance and Reconnaissance

"Control and Guidance of Multiple Air-Vehicle Systems" [13], "An Analytic Model to Evaluate the Influence of Uncertainty on the Cooperative Search Behaviors of Autonomous UAVs" [24], "A Dynamic Path Generation Method for a UAV Swarm in the Urban Environment" [25] and "Collaborative UAV Exploration of Hostile Environments" [26].

However, despite having garnered significant research interest, the literature review could only find evidence of development of testbeds to demonstrate a number of crucial technologies, with weak links suggesting how the products of these development efforts could be integrated. The United States Army has envisioned a single operator operating multiple UAVs in their UAS Roadmap [1] but stopped short of giving details as to how they envisioned the UAVs would collaborate, the nature of operations envisioned or the way such an operation is conducted. There are reasons to believe certain activities are still needed to complete the transition from research interest to a deployed system.

The deployment of the UAS in cooperative/collaborative applications requires interoperability between systems. In addition, the United States Air Force UAS Flight Plan mentioned that future UAS should be multi-mission, all weather, network-centric, and modular and should have an open architecture and employ leveraging of appropriate levels of autonomy. A similar view is echoed by the United States Army UAS Roadmap. Collectively, the requirement for collaborative operations and multi-mission UAV platforms poses a design challenge which warrants detailed study of needs, requirements, limitations and constraints, coupling and cohesion, and emergent behavior. Without a doubt, the analysis to be conducted is characteristic of a Systems Engineering Study[45].

[4] Systems Engineering as defined by International Council on Systems Engineering (INCOSE): Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focus on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem: Operations, Cost & Schedule, Performance, Training & Support, Test, Disposal, Manufacturing. Systems Engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process from concept to production to operation. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs. For more information, please see the INCOSE website at http://www.incose.org/practice/whatissystemseng.aspx.

The complexity of the system[6] or system of systems[7] in consideration also requires analysis at various levels of abstraction, starting from the highest level "world view."

B. MOTIVATION OF STUDY

The challenge of successfully deploying a quality system is inherently complex. Systems engineering is an interdisciplinary approach that advocates applying a holistic view to a system. The breadth and depth of a practitioner's knowledge limits how "holistic" a view he can adopt, potentially impacting the quality of the design or the completeness of a feasibility study, gap analysis or assessment which contributes to the quality and success of a system.

The task of accumulating knowledge is both challenging and time consuming, requiring consolidation of information from various sources and across various domains. For example, roadmaps and technical papers can provide information at different levels of depth. Roadmaps are a good source of information regarding desired state and envisioned usage. Technical papers can be a source of information at a greater level of resolution, such as specific designs that have been implemented and assessed, the pros and cons of each design approach, etc. Broad knowledge requires consolidation of information across various technical and non-technical domains. To add to the challenge, different areas of applications potentially require different sets of knowledge expertise. In addition, the process of translating ideas into deployed systems usually involves

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[5] Systems Engineering as proposed by Gary O. Langford in his book *Engineering Systems Integration: Theory, Metrics, and Methods*: The charter of systems engineering is to create and express ideas and integrate components into systems that are referred to as products or services. The essence of system engineering is to unbound the seemingly bounded, broaden the concepts to beyond recognition, open the solution domain to include the ridiculous, and consider the issues and problems in an abstract space rather than as they are posed or presumed to be real. No other discipline or field carries with it that worldview.

[6] The author adopts the description of a system as: "A system is a bounded, stable group of objects exhibiting intrinsic emergent properties that through the interaction of energy, matter, material wealth, and information provide functions different from their archetypes" in the context of this discussion. This definition of system is proposed by Gary O. Langford in his book *Engineering Systems Integration: Theory, Metrics, and Methods*.

[7] System of systems is proposed by Gary O. Langford in his book *Engineering Systems Integration:Theory, Metrics, and Methods*. A system of systems is a set of systems that are both integrated and interoperable to achieve a set of metasystem functions in which all the component systems participate (to varying degrees).

conducting numerous studies which not only requires domain knowledge, but also time and other resources.

This thesis attempts to conduct an ambitious consolidation of information with regard to deploying multi-UAVs in cooperative systems. The intention is to lay the ground work for future conduct of gap analysis and other Systems Engineering activities. Although many documents regarding UASs exist, the documents are either not explicitly written to address multi-UAV collaborative operations, or they are not written with the intention of supporting the conduct of systems engineering activities, or they warrant a significant price tag, or they represent a combination of the respective shortcomings. At the same time, this thesis also seeks to understand the current status of research, development and assessment efforts that impact the progress of systems adopting the multi-UAV cooperative concepts towards deployment. Finally, this thesis seeks to understand the operating challenges involved in using state-of-the-art technology to enhance situational awareness and potentially avoid collision.

C. METHODOLOGY AND APPROACH

1. System Engineering

Many different definitions for Systems Engineering exists, some representative examples include the definition used by the International Council on Systems Engineering (INCOSE) [27] and the definition by Gary O. Langford [28].

> Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focus on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem: Operations, Cost & Schedule, Performance, Training & Support, Test, Disposal, Manufacturing. Systems Engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process from concept to production to operation. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs. [27]

> The charter of systems engineering is to create and express ideas and integrate components into systems that are referred to as products or services. The essence of system engineering is to unbound the seemingly

> bounded, broaden the concepts to beyond recognition, open the solution domain to include the ridiculous, and consider the issues and problems in an abstract space rather than as they are posed or presumed to be real. No other discipline or field carries with it that worldview. [28]

Without being restricted to any single definition, Systems Engineering involves applying a holistic view or "worldview" and adopting multiple perspectives when performing tasks, anticipating issues and dealing with issues during life cycle of the system. Systems Engineering deals with the cost, planning, schedule and management aspect of a system development problem, as well as the actual design and development process. Within the context of system life cycle activities, the strategy and processes chosen for a group of activities has impact on other activities. For example, an incremental or evolutionary strategy to deploy a system will like require the design which is less complex to modify. A complex design will likely impact project management, requiring process and plans that facilitate feedback and testing. The complexity of Systems Engineering and the relationship of the systems engineering process with one another are shown in Figure 1.

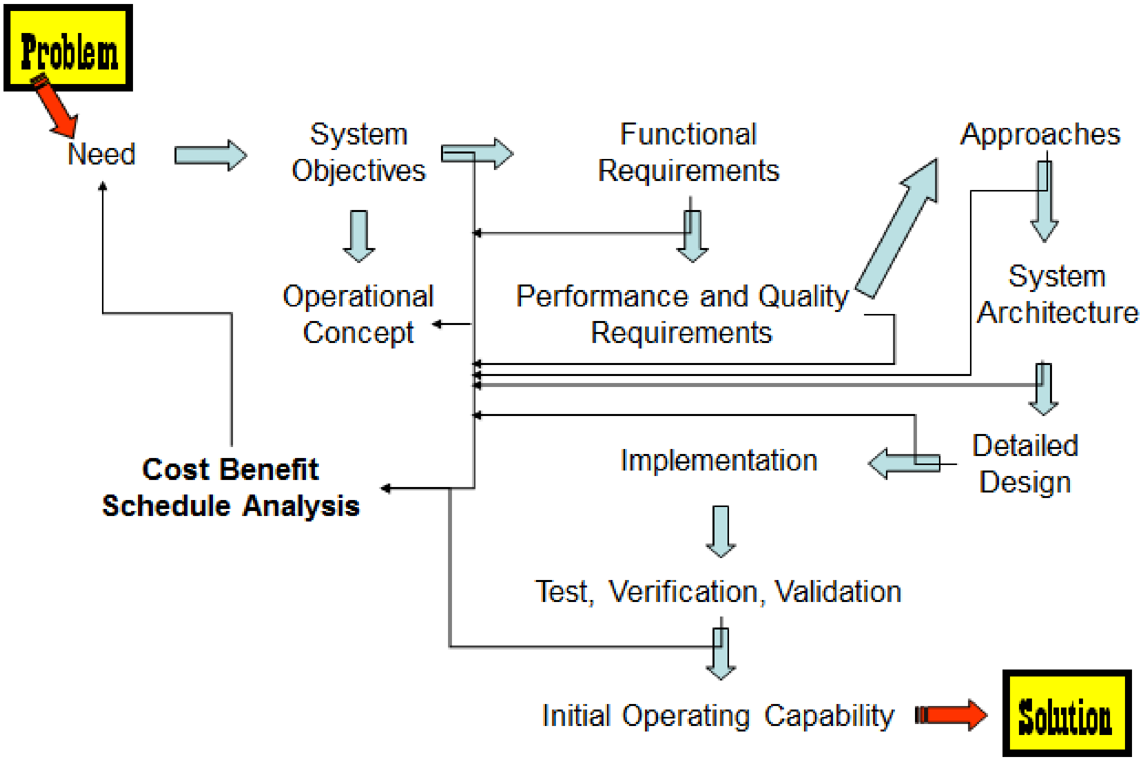

Figure 1. System Engineering Process. From [29].

Systems Engineering is the methodology accepted in this thesis as the approach to enable the realization of a successful system [27]. At the same time, the information consolidated within this thesis is also intended to assist the Systems Engineering practitioner involved in the "Multi-UAVs system" area of work in the conduct of systems engineering work. These activities include system design, system assessment, feasibility studies, system development, system integration, system validation and system testing.

This thesis focuses on consolidating information that facilitates concept development and design development activities. If the objective is to facilitate project management and planning activities, additional information such as lessons learnt from past UAS development projects and schedule and cost related information of past UAS projects is likely required.

2. Gap Analysis

The notion of a gap represents the difference between a desired state and the current state. Gary O. Langford explains a gap as "what you desire against what you have" [29]. The gap is manifested in the difference between what is perceived important against what you have or what exists in contrast to what is expected [29].

Gap analysis has been termed a structured approach to overcome dissatisfaction with current states, referenced to desired future states [29]. Gap analysis is a means to select the appropriate Systems Engineering process model and modify it to match the means and method and type of developing a product [29]. Gap analysis loosely defines a method for identifying the degree to which the current system satisfies a set of requirements, and the goal of the analysis is to align anticipated outcome with a future reality that can be achieved [29].

The notion of gap in the context of the Department of Defense acquisition process and potential types of solutions to "close the gap" is described in *Gap Analysis: Rethinking the Conceptual Foundations* by Gary O. Langford et al. [30].

> For the Department of Defense, Gaps are defined in terms of functional areas; relevant span and domain of military operations; intended effects; temporal matters; policy implications and constraints. Further all gaps are defined in terms of capability. The Joint Capabilities Integration Development System (JCIDS – the formal U.S. DoD procedure which defines acquisition requirements and the criteria to evaluate weapon systems) was implemented to specifically address capability gaps. But not all capability gaps require a material solution set. Changes or enactments of Doctrine, Organization, Training, Materiel, Leadership and education, Personnel, and Facilities (DOTMLPF) are also considered to close Gaps. Such considerations are formally evaluated before recommending the start of a new acquisition effort (CJCSI 3170.01E and CJCSM 3170.01B). In essence functional capabilities are assessed to identify gaps.

Gap analysis requires adopting multiple perspectives to view the problem and also to assess potential solutions (material solutions, changes or enactments of doctrine, organization, training, materiel, leadership and education, personnel, and facilities [30]) to achieve the desired state. Figure 2 shows the information inputs to a gap analysis and the types of analysis performed for gap analysis in the context of DoD acquisitions.

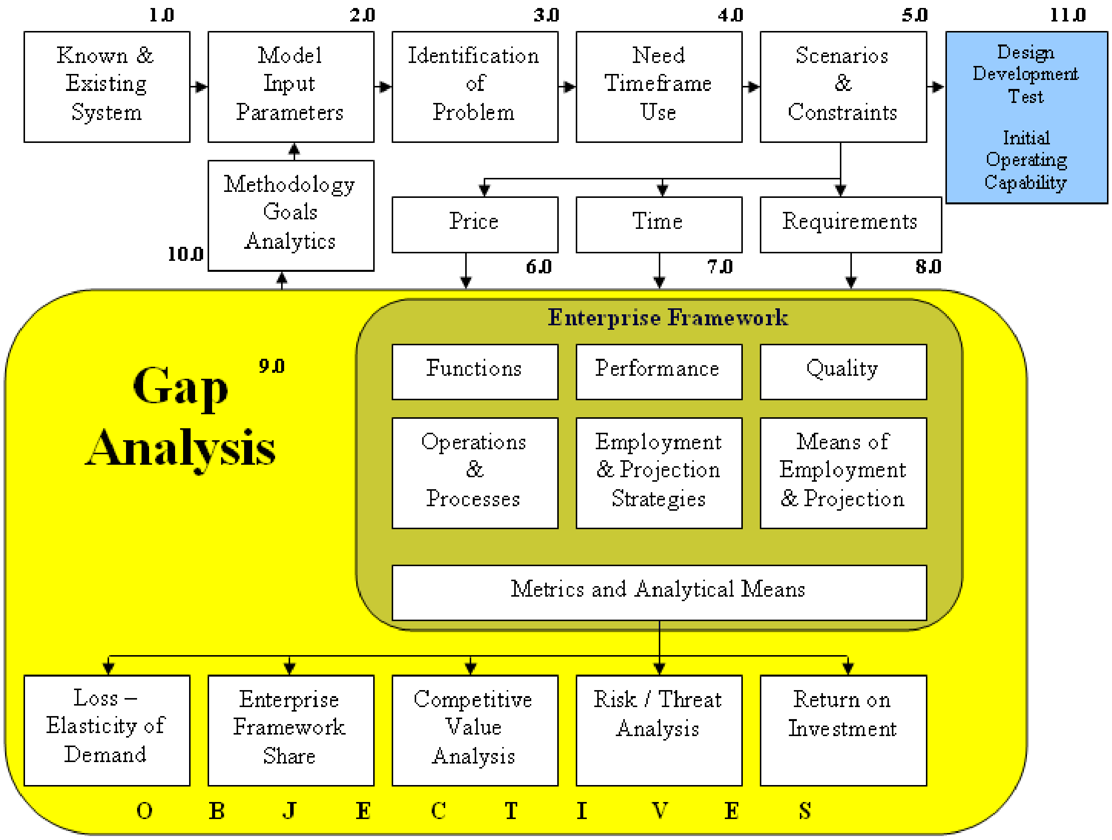

Figure 2. Gap Analysis for DoD Acquisition. From [29].

In the context of this thesis, the term gap[8] refers to the difference between the current state for a multi-UAVs system and desired state (field deployed). The primary purpose of the report is to lay the groundwork for future analysis in multi-UAV analysis to close the gap between existing research and efficient multi-UAV operations. This report focuses upon blocks 1.0, 2.0, 3.0, 4.0, and 5.0.

D. REPORT ORGANIZATION

This thesis is divided into two major sections. The first section (Chapters II to IV) examines multi-UAVs cooperation, with a secondary focus on unmanned and manned

[8] The term “gap” as used in the title *Closing the Gap Between Research snd Field Applications for Multi-UAVs Cooperation Mission.*

systems cooperation. Chapter II focuses on providing the overview information regarding the UAS and summarizes envisioned applications of the UAS, primarily based on various roadmaps found in public domain. Chapter III focuses on potential areas for collaborative applications and documents relevant information and references to various aspects within each area of application. Chapter IV seeks to document the challenges of the respective areas identified in Chapter III, understand and document the rationale behind the interest in the respective areas and document the factors that affect the perceived value of specific system designs. The same chapter also seeks to document relevant information relating to a number of technological enablers that were perceived as important and documents references providing description of greater details. Finally, the chapter also provides an interpretation of the status of a number of potentially important areas to be considered when performing systems engineering related activities, such as system design or development strategy.

The second section (Chapter V) describes the conduct of the experiment to study the operating challenges in using the ADS-B and EO/IR camera for situational awareness. The chapter describes the components used in the conduct of the experiment and the design of the experiments and includes a discussion on operational requirements.

E. RESEARCH QUESTIONS

Main Question:

- In order to set the stage for future Systems Engineering gap analysis, what is the state of research related to technology readiness and efficient deployment of multi-UAV operations?
- Subsidiary Questions:
- What are the operational areas of interest for multi-UAV operations?
- What are the reasons justifying the interests and the needs addressed by the respective areas of interest?
- What are the technical areas of interest for multi-UAVs operations?
- What are the implementation challenges, both technical and non-technical, to deploying multi-UAVs systems?

- Can a systems engineering perspective be adopted to study components for enhancing situational awareness and derive the operating challenges and operating requirements?

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II. DESCRIPTION AND HISTORY OF UNMANNED AERIAL SYSTEMS (UAS)

A. HISTORY OF UAS FOR UNITED STATES MILITARY APPLICATIONS

The research and employment of UAVs by the United States military services date as far back as 1917 [31]. Other common descriptive terms for these aircraft are drones, robot planes, Remotely Piloted Aircraft (RPA). Collectively, the UAV and other ground components are commonly referred to as an Unmanned Aircraft System or Unmanned Aerial System (UAS).

Historically, the first UAS was tested by the United States during World War I and deployed in combat during the Vietnam War. More recently, the United States procured UASs in significant numbers and deployed these systems in conflicts such as Kosovo (1999), Iraq (since 2003) and Afghanistan (since 2001) [31]. The success of UAS use by the Israeli military in Lebanon (1982) captured the interest of U.S. observers and encouraged then Navy Secretary to acquire UAS capability for the Navy [31]. Interest was also aroused in other parts of the Pentagon, marking the transition from experimental projects to acquisition programs [31].

The United States' initial UAS capabilities were acquired from Israel [31]. Successful application of these platforms identified additional potential and encouraged new platforms to be acquired to perform new mission activities.

> Initial U.S. capabilities came from a platform acquired from Israel. One such UAS, Pioneer, emerged as a useful source of intelligence at the tactical level during Operation Desert Storm, when Pioneer was used by Navy battleships to locate Iraqi targets for its 16-inch guns. Gulf War experience demonstrated the potential value of UAS, and the Air Force's Predator was placed on a fast track, quickly adding new capabilities. Debuting in the Balkans conflict, the Predator performed surveillance missions such as monitoring area roads for weapons movements and conducting battle damage assessment. Operations in Iraq and Afghanistan have featured the Air Force's Global Hawk, as well as adding new missions that allows Predator to live up to its name—armed reconnaissance [31].

B. DESCRIPTION OF UAS

1. Components of UAS

A UAS typically comprises an aerial component (UAV) and the ground components. Figure 3 shows an overview of the components of one UAS (AAI Shadow 200).

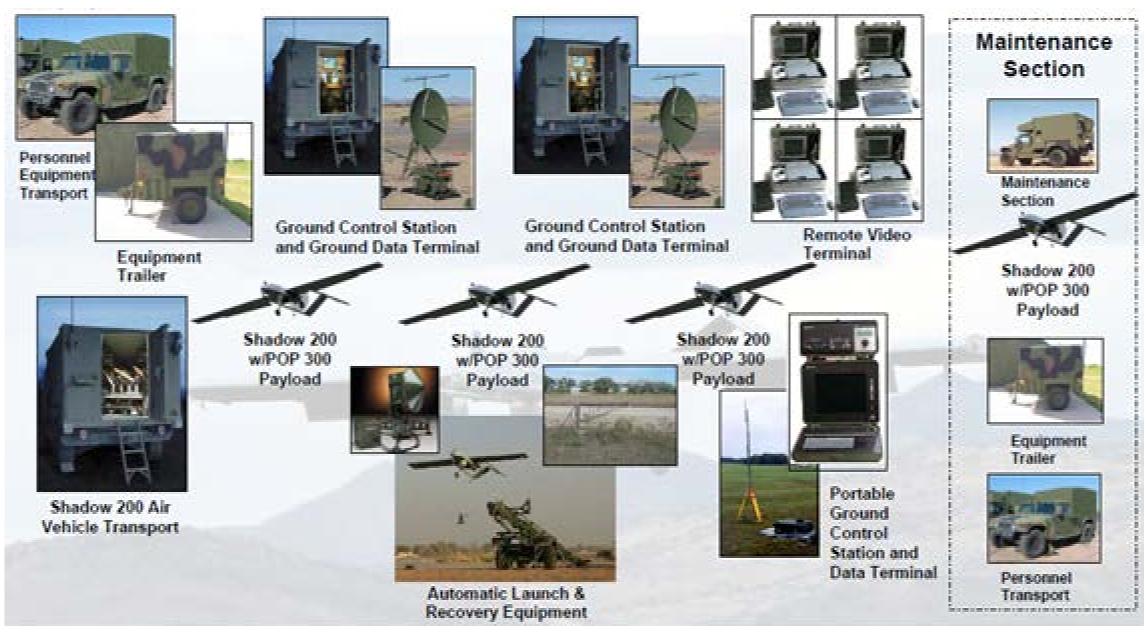

Figure 3. AAI Shadow 200 UAS System. From [32].

a. UAV / RPA

The United States Department of Defense (DoD) defines UAVs as powered, aerial vehicles that do not carry a human operator, use aerodynamic forces to provide vehicle lift, can fly autonomously or be piloted remotely, can be expendable or recoverable, and can carry a lethal or nonlethal payload [31].

The aircraft is used as a platform to carry payloads according to operational needs. Examples of payloads can be cameras, radars, communication relay or offensive weapons. Numerous UAV platforms have been developed to meet different types of operational requirements. Three parameters commonly used to categorize UAVs are operating altitude, operating endurance (flight duration) and weight/size. The wingspan can range from 30cm or less for Micro UAVs to 35.4m or more in the case of the Global Hawk and other similar class UAVs. The aircraft can be fixed wing, quadrotor, helicopter and other hybrid forms as shown in Figure 4. Examples of common launch mechanisms are runway takeoff, launcher assisted, hand launched and vertical take-off. Examples of common recovery mechanisms are runway landing, arresting hook, vertical landing, parachute landing and airbag system (cushioned landing).

Figure 4. Example of fixed wing, quadrotor, helicopter and other hybrid forms of UAVs (clockwise from top left). From [33–36].

b. Payloads

UAV payloads are generally sensors, communication terminals, and in some cases, offensive weapons.

(1) Sensors

Typical sensors payload are Electro-Optics/Infra-Red (EO/IR) camera and Synthetic Aperture Radar (SAR). Figure 5 shows an example of each of the respective sensor payloads.

Figure 5. Example of SAR and EO/IR (left to right). After [37] and [38].

(2) Communication Terminals

Typical communication payloads are data terminals for a direct communication link with the Ground Control Station (GCS), data terminals to perform communication relay and satellite communication data terminals for indirect communication links over extended operational range.

(3) Offensive Weapons

A well-known offensive capable UAV platform is the Reaper UAV (MQ-9). The Reaper UAV is capable of carrying AGM-114P Hellfire missiles, GBU-12 Paveway II laser-guided bombs and GBU-38 Joint Direct Attack Munition (JDAM) [39].

c. Ground Components

(1) Logistics for UAV Launch/Takeoff and Recovery

Logistics for UAV launch and recovery is only applicable to a UAV platform which requires specialized equipment for its launch and/or recovery operations and may not be applicable to some UAV platforms. Examples of specialized launch equipment are Automatic Takeoff and Landing equipment for UAVs capable of automated takeoff and landing and the UAV Launch System for UAVs requiring assisted launch. An example of specialized recovery equipment is an arresting hook system. Figure 6 shows an example of a UAV Launch System and a UAV Recovery System, respectively.

Figure 6. Example of UAV Launch System and UAV Recovery System (left to right). After [40] and [41].

(2) Ground Control Station (GCS)

GCS refers to the component which allows the operator to operate the UAV and/or other components of the UAS. In the case of smaller class UAVs, the GCS can be a unit or mobile computing device (e.g., a rugged laptop), running operating software that provides the interface for UAS operation. A GCS for the larger class of UAV is usually more complex, consisting of multiple operating consoles/terminals contained within an enclosed environment. Also considered as part of the GCS is support equipment such as a power generator, air conditioning, network switches and other network components, circuit breaker and computing servers. A complex GCS usually has at least two operating consoles which allows flight and payload operations to be handled by different operators. Consoles used by an Image Analyst to exploit and extract information out of raw sensor products can also be integrated as part of the GCS.

(3) Ground Data Terminal (GDT)

GDT refers to the component that allows communication between the ground components and the airborne components. A GDT establishes and maintains the link with the airborne communication terminals carried by the UAV. In the case of an indirect communication link (e.g., relayed by satellites), the GDT establishes and maintains the link with the relay component.

2. UAV Categorization and Corresponding Examples of UAV Platform

Various ways to categorize UAVs exist. A popular approach is to classify UAVs based on their technical specifications such as mass, operating altitude and endurance, and to refer to UAVs in loosely categorized groups such as Micro, Mini, Tactical, Medium Altitude Long Endurance (MALE) and High Altitude Long Endurance (HALE). Ronald E. Weibel included a detailed description of these respective groups in his thesis [42] . It is recommended to refer directly to Weibel's work for the description [42].

The United States Army and the United States Air Force use a similar classification method as the one shown in Table 1 in their respective roadmaps [1] and [20].

<table>
<tr><th>UAS Category</th><th>Maximum Gross Takeoff Weight (lbs)</th><th>Normal Operating Altitude (ft)</th><th>Speed (KIAS)</th><th>Current / Future Representative UAS</th></tr>
<tr><td>Group 1</td><td>0-20</td><td>< 1,200 AGL</td><td>100 kts</td><td>Wasp III, FCS Class I, TACMAV, RQ-14A/B, BUSTER, BATCAM, RQ-11B/C, FPASS, RQ-16A, Pointer, Aqua Terra, Puma</td></tr>
<tr><td>Group 2</td><td>21-55</td><td>< 3,500 AGL</td><td rowspan="2">< 250</td><td>Vehicle Craft Unmanned Aircraft System, ScanEagle, Silver Fox, Aerosonde</td></tr>
<tr><td>Group 3</td><td>< 1320</td><td rowspan="2">< 18,000 MSL</td><td>RQ-7B, RQ-15, STUAS, XPV-1, XPV-2</td></tr>
<tr><td>Group 4</td><td rowspan="2">> 1320</td><td rowspan="2">Any Airspeed</td><td>MQ-5B, MQ-8B, MQ-1A/B/C, A-160</td></tr>
<tr><td>Group 5</td><td>> 18,000 MSL</td><td>MQ-9A, RQ-4, RQ-4N, Global Observer, N-UCAS</td></tr>
</table>

Table 1. UAS classification as presented in the United States Air Force UAS Flight Plan. From [20].

C. APPLICATIONS OF UAS

A traditional view regarding the advantage of the UAS over manned aircraft is in the area of "dull," "dirty" or "dangerous" [31] and [43]. The United States Army identified three critical capabilities that the UAS can provide for current and future force.

> Unmanned aircraft systems can provide three critical capabilities for the Army's current and future force. First, UAS reduce risks to the Soldiers in the current fight (e.g., explosive hazard detection and neutralization). Second, UAS reduce the workload on the Soldiers by performing routine missions and enable sustained high tempo operations (e.g., routine surveillance of forward operating bases). Third, UAS provide emerging capabilities for extended range or standoff reconnaissance operations. [1]

The UAS roadmap released by the United States Office of Secretary of Defense in 2005 included a table summarizing UAS application up to the year 2005 (Table 2). The same document also mentioned that UAS have matured to the point where one no longer needs to look for niche missions for these systems [43].

> UA have matured to the point where one no longer needs to "look for niche missions"… The U.S. can develop a UA to accomplish almost any mission imaginable. Instead of asking "Can we find a mission for this UA?" one will ask "Why are we still doing this mission with a human?" [43]

The types of missions that have been and can be fulfilled by UAS are adequately described in roadmaps published by the various military services. A quick list of examples of such roadmaps are *Unmanned Aircraft Systems Roadmap 2005 – 2030* by Office of the Secretary of Defense [43], *"Eyes of the Army" U.S. Army Roadmap for Unmanned Aircraft Systems 2010–2035* by U.S. Army UAS Center of Excellence [1], *United States Air Force Unmanned Aircraft Systems Flight Plan 2009–2047* by Headquarters United States Air Force [20] and *Unmanned Systems Integrated Roadmap FY2011–2036* by United States Department of Defense [2]. The next section will only highlight a number of well discussed or valued UAS mission areas that were identified as relevant to the context of the topic. It is by no means an adequate reference for the types of UAS mission areas being considered.

Requirements	Justification for UA Use			UA Experience
(Mission Areas)	"Dull"	"Dirty"	"Dangerous"	(UA/Payload, Place Demonstrated, Year)
ISR	x		x	Pioneer, Exdrone, Pointer/Gulf War, 1990-91 Predator, Pioneer/Bosnia, 1995-2000 Hunter, Predator, Pioneer/Kosovo, 1999 Global Hawk, Predator, /Afghanistan, Iraq 2003 – Present Hunter, Pioneer, Shadow/Iraq-2003-Present
C2/Communications	x			Hunter/CRP, 1996; Exdrone/TRSS, 1998 Predator/ACN, 2000
Force Protection	x	x	x	Camcopter, Dragon Drone/Ft Sumner, 1999 FPASS, Dragon Eye, Pointer, Raven, Scan Eagle/Iraq -Present
SIGINT	x		x	Pioneer/SMART, 1995 Hunter/LR-100/COMINT, 1996 Hunter/ORION, 1997 Global Hawk/German Demo, 2003; Iraq, 2004 - Present
Weapons of Mass Destruction (WMD)		x	x	Pioneer/RADIAC/LSCAD/SAWCAD, 1995 Telemaster/Analyte 2000, 1996 Pointer/CADDIE 1998 Hunter/SAFEGUARD, 1999
Theater Air Missile Defense (TAMD)	x		x	Israeli HA-10 development, (canceled) Global Hawk study, 1997
SEAD			x	Hunter/SMART-V, 1996 Hunter/LR-100/IDM, 1998 J-UCAS/TBD
Combat Search and Rescue (CSAR)			x	Exdrone/Woodland Cougar Exercise, 1997 Exdrone/SPUDS, 2000
Mine Counter Measures (MCM)			x	Pioneer/COBRA, 1996 Camcopter/AAMIS, 1999 (Germany)
Meteorology and Oceanography (METOC)	x	x	x	Aerosonde/Visala, 1995 Predator/T-Drop, 1997 Predator/BENVINT ACTD, 2002
Counter Narcotics (CN)	x		x	Predator/Ft Huachuca, 1995 Pioneer/So. California, 1999 Hunter, Shadow/Ft Huachuca, 2003-2004
Psychological Ops			x	Tern/Leaflet Dispensing, 2004
All Weather/Night Strike			x	DASH/Vietnam, 1960s Predator/Afghanistan/Iraq, 2001 Global Hawk/Iraq, 2003
Exercise Support	x			Predator/Joint Operational Test Bed System (JOTBS), 2002
Anti Submarine Warfare	x			DASH, 1960s
Navigation	x			Hunter/GPS Pseudolite, 2000
Table is not all inclusive				

Table 2. Example of UAS mission areas up to year 2005. From [43].

1. Intelligence, Surveillance, Target Acquisition and Reconnaissance

Intelligence, Surveillance, Target Acquisition and Reconnaissance (ISTAR) is probably the most recognized mission area for UAS. The UAV has been as a platform to carry a wide range of sensor payloads for ISTAR applications. Long endurance capabilities of MALE and HALE UAVs and the ability to rotate operating crews, located remotely on the ground, allowed these systems to be operated for long durations at an extended range and at low risk to the crew. Smaller UAVs are also recommended as an option to “get in close” to obtain high resolution imagery or to detect “weak signal” targets [43].

2. Provide Battlespace Awareness

Battlespace Awareness is based on knowledge and understanding of a prescribed area of operations (AO), usually obtained through means of ISTAR activities. It is focused on keeping combat commanders aware of recent and current events in their battlespace and assisting commanders in predicting near term events in the battlespace. According to the U.S. Army roadmap, Reconnaissance and Surveillance “remained the number one combatant commander priority for unmanned systems.

> **Reconnaissance and Surveillance.** This remains the number one combatant commander priority for unmanned systems. While the demand for full motion video (FMV) remains high, there is an increasing demand for wide-area search and multi-intelligence capability. Processing, exploitation, and dissemination (PED) remains a key area highlighting the need for interoperability. [1]

The UAS is employed across all U.S. Army echelons as dedicated or organic support to tactical, operational and strategic operations [1].

3. Target Designation and Strike

A UAV can be used to perform laser designation on a target. Platforms such as the MQ-1 Predator are also capable of delivering strike capabilities. The value of such a capability was validated in Operation Enduring Freedom and Operation Iraqi Freedom where it made possible a rapid response to fleeting targets [43]. In the roadmap from the Office of Secretary of Defense, the terms “armed reconnaissance” or “persistent strike” were used to describe this capability. The development of the MQ-9 Predator introduced greater weapons capability.

4. Signals Intelligence (SIGINT)

SIGINT refers to the gathering of intelligence by means of signal interception. Examples of a UAV platform with SIGINT capability are the Hermes 450, MQ-1 Predator, RQ-4 Global Hawk and Shadow 200 (Electronic Intelligence, ELINT) [44].

5. Security and Risk Reduction to Force

UAV use to detect a potential explosive hazard and other threats and to maintain surveillance for suspicious activities over convoy or ground patrol routes is an important aspect of providing security and reducing risk for ground forces movements. The successful use of the T-Hawk UAV for counter Improvised Explosive Device (IED) purposes in Afghanistan was shared by Major Thomas Donohoe in the UV Europe 2011 Conference held in Brussels. The T-Hawk is part of the Talisman system employed by the UK military in Route Proving and Clearance Manoeuvre Support in Afghanistan [45].

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III. MULTI-UAV COLLABORATION RESEARCH

A. URBAN OPERATIONS

The need for military forces to operate in an urban environment is undeniable. There were a number of papers that discuss improving areas of technology that could allow multi-UAVs to be the solution to some challenges faced when operating in the urban environment. Examples of popular areas, with adequate references in public literature, are discussions of improved autonomy, effects of the urban environment on communication, overcoming communication challenges and Global Positioning System (GPS) denied operations.

Improving UAV autonomy can be further decomposed into sensing, path planning (collision avoidance and path optimization), task allocation, collaborative control and guidance, etc. "Control and Guidance of Multiple Air-Vehicle Systems" by a team of researchers from National University of Singapore and Nanyang Technological University documents the result of their investigation into three key areas of control and guidance of multiple air-vehicles [13], one of which is GPS-less, map-less, vision based navigation. Collaborative coverage and search and de-centralized formation flight control are the other two key areas of focus. Another example is "Collision-free Multi-UAV Optimal Path Planning and Cooperative Control for Tactical Applications" by Kevin P. Bollino and L. Ryan Lewis [9]. "Real-time Multi-UAV Task Assignment in Dynamic and Uncertain Environments" discuss a study using the Consensus Based Bundle Algorithm (CBBA) for task assignment with extension to handle obstacle avoidance and reduced task planner sensitivity to sensor measurement noise [8].

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Willy Lock studied the effects of radio wave propagation in urban areas on UAV-GCS command and control in 2003 [46]. The thesis studied the effects of having up to three UAVs. Chua Chee Nam wrote about “Integration of Multiple UAVs for Collaborative ISR Missions in Urban Environments” in 2012 [23]. In his thesis, Chee Nam demonstrated and investigated a concept of operation involving up to two quadrotor UAVs, capable of dynamic reconfigurations and using the Inverse Dynamic in Virtual Domain method as control method in a laboratory environment.

Other examples of urban UAV use include “Autonomous Surveillance in Complex Urban Environments” [47], “Network-Centric Systems for Military Operations in Urban Terrain: The Role of UAVs” [48], “A Dynamic Path Generation Method for a UAV Swarm in the Urban Environment” [49] and “Multi-UAV Sensing over Urban Areas via Layered Data Fusion” [50].

B. COMMUNICATIONS SUPPORT

The UAV can be used as a communication relay in multiple scenarios. Exploration of the UAV as a communication relay is a topic that has substantial history. Quoting the UAS roadmap published by the Office of the Secretary of Defense (United States) in 2005 [43], a detailed study, dated 4 November 1997, was conducted by the Office of Secretary of Defense/C3I on Unmanned Aerial Vehicles as Communications Platforms.

Boeing announced the successful demonstration of their ScanEagle UAV as a communication relay as early as 2004 [51]. Northrop Grumman was awarded the contract to develop the Battlefield Airborne Communications Node (BACN) payload in 2005, which was eventually integrated with the Global Hawk UAV produced by the same company [52]. BACN is an information gateway that bridges and extends voice communications and battlespace awareness information from numerous sources using a suite of computers and radio systems [52]. In the commercial domain, the Aerostar UAV has been successfully deployed to relay TV broadcasts for Israel's Channel 2 [53].

Anders Holmberg and Per-Magnus Olsson in "Route Planning for Relay UAV" discuss their algorithm for solving the relay UAV positioning and planning problem for a scenario using a UAV as an intermediary node to bridge the communication between the surveillance UAV and the ground station [11]. A recent paper which discusses the application of UAV as communication support is "Communication Provision for a Team of Remotely Searching UAVs: A Mobile Relay Approach." It discusses a study based on a scenario using of a relay UAV to bridge the communication between a team of small rotor-craft UAVs deployed for Wilderness Search and Rescue and the base station by providing a delay tolerant link [54]. The use of a relay UAV was also proposed in the scenario considered by Chua [23].

One area of research focus is the use of multiple nodes to form a wireless mesh network. UAVs can be considered for application as communication mesh network nodes. Mark G. Richard documented his work with regard to developing self-tuning extremum control techniques developed for UAV communication relays to be used with multiple relay nodes in a distributed wireless sensor network [55].

C. COLLABORATIVE SENSING

Lawrence Liang studied the effect of various parameters on the conduct of collaborative sensing (detection and classification) on Time Critical Targets using agent based simulation [56]. The three preceding theses by Raffetto [57], Berner [7] and McMindes [58] were mentioned as references. Our study made use of Map Aware Non-uniform Automata (MANA) to construct a scenario modified from Raffetto's thesis.

Kevin K. McCadden and Christopher A. Nigus document an effort to create a decision aid, utilizing Dynamic Programming and Bayesian Updating, which recommends an efficient search path for multiple UAVs searching for multiple moving targets [59]. An additional research example is a dissertation by Andrew G. Shem, which presents a framework within which it is possible to represent, model and measure uncertainty [24].

> The key problem motivating this work was the need to understand how information uncertainty influences cooperative UAV performance. To gain this understanding, we developed a framework within which we could represent, model, and measure uncertainty. Such a framework gives a UAV system engineer useful tools to help represent, model, and understand information uncertainty in the context of cooperative UAVs searching for moving targets. The framework we derived in this thesis provides a theoretical, probabilistic description of how uncertainty influences performance of cooperative UAV teams searching for moving items. [24]

D. SWARM

UAV swarm is another popular area of research. UAV swarm typically refers to operating multiple collaborative small UAVs in close proximity to achieve a common mission objective. The United States Air Force expressed their interpretation of the near-term concept of swarming in their UAS Flight Plan [20].

> The near-term concept of swarming consists of a group of partially autonomous UAS operating in support of both manned and unmanned units in the battlefield while being monitored by a single operator. Swarm technology will allow the commander to use a virtual world to monitor the UAS both individually and as a group. A wireless ad-hoc network will connect the UAS to each other and the swarm commander. The UAS within the swarm will fly autonomous to an area of interest (e.g., coordinates, targets, etc.) while also avoiding collisions with other UAS in the swarm. These UAS will automatically process imagery from low level users and will "detect" threats and targets through the use of artificial intelligence (AI), sensory information and image processing. Swarming will enable the UAS network to deconflict and assign the best UAS to each request. [20]

Although able to find a description of the guiding concept regarding swarm, no officially endorsed specific applications for UAV swarms in the documents reviewed. The potential use of UAV swarms can be inferred from the scenarios assumed in various papers published to discuss the result of various technological enablers. This following section provides a brief summary of potential applications for UAV swarms, namely wide area search, electronic warfare, offensive and defensive.

1. Wide Area Search

Although organized as a separate section to indicate that UAV swarms can be applied for wide area search, UAV swarms for wide area search is viewed in the context of this thesis as an extension of Collaborative Sensing. Enabling technology such as methods to determine the search path to maximize the probability of target detection is expected to be applicable to both application domains. One possible differentiating factor might be the difference between centralized and distributed control for the UAVs involved in the search.

UAV swarms can be used to improve the efficiency of a wide area search. "Collaborative UAV Exploration of Hostile Environments" describes a study conducted with the objective to minimize exploration time, avoid damage by sharing information about threats and be robust to the failures of individual UAVs [60]. In the same paper, results of simulations concluded that exploration time decreases with the number of UAVs used, up to an optimal number, above which the exploration time increased. It was concluded by the authors that the observation could be due to phenomena such as frontier starvation and additional communication needs.

2. Electronic Warfare (EW)

Use of UAVs for EW was briefly mentioned in a report released by the Library of Congress in 2006 [61].

> Miniaturized radio-frequency components and small-form processor boards have the potential to drive the development of EW payloads for small UAVs. Sweden's Saab Technologies has worked with Australia's Defense Science and Technology Organisation to develop EW payloads for UAVs. The Australian-built Aerosonde Mark III … has participated in EW experiments transmitting "real-time emitter bearings and pulse analysis data to the ground station. [61]
>
> Germany's Rheinmetall Defense Electronics (RDE) also is working on EW applications for large UAVsAccording to RDE, its products provide superior information-gathering capabilities by detecting and jamming

> VHF/UHF radio, satellite communications systems, mobile radios, line-of-sight radios, and radar activity…RDE also says its electronic warfare UAVs can be operated in a swarm of four units. [61]

3. Offensive

The Library of Congress research report cited Russian Major General Igor Sheremet's description on how swarms of UAVs could be used to carry out attacks on an opponent's Network Centric Warfare (NCW) systems [61]. The was also a thesis which quoted a Maritime Expeditionary Security Force Initial Capabilities Document mentioning the need for point defense against limited air threats (which includes small radar cross-section targets such as UAVs) that penetrate Sea Shield local air defense umbrellas [62]. The use of UAV swarms to overwhelm the defense of a single high value target through sheer numbers can be considered a credible threat. A group of NPS students conducted a study regarding the ability of the Arleigh Burke-Class Aegis Guided-Missile Destroyer (DDG) to defend against a swarm of UAVs fitted with IEDs and made recommendations regarding system alternatives to improve the DDG's defense against such attacks [62].

> One of the core capabilities identified in the MES Initial Capabilities Document (ICD) is to "detect, identify, engage, and destroy Level I and Level II hostile air, surface, subsurface, and ground targets, day and night, and in most weather conditions in the littoral battle space." Currently, MES forces are unable to adequately fulfill this capability. An unmanned aerial vehicle (UAV) can carry missiles or act as an Improvised Explosive Device (IED), and could be employed by terrorists (Level I threat) or be part of irregular (Level II threat) forces. [62]

4. Defensive

The use of UAV swarms to defend against swarm attacks was the scenario considered by Michael Day, who wrote his thesis regarding the study of the effectiveness of various task assignment methodologies for a team of UAVs seeking to thwart an attack by another team of aggressor UAVs [63]. In his thesis he also studied the effects of other factors on the effectiveness of the defending UAV swarm [63]. A similar concept of UAV swarm against UAV swarm was also used by Umit Soylu as the scenario of reference for his thesis [64].

E. LOYAL WINGMAN

In the loyal wingman application, the United States Air Force UAS flight plan described the UAS as a loyal wingman for a manned aircraft.

> Loyal wingman technology differs from swarming in that a UAS will accompany and work with a manned aircraft in the AOR to conduct ISR, air interdiction, attacks against adversary integrated air defense systems (IADS), offensive counter air (OCA) missions, command and control of micro-UAS, and act as a weapons "mule," increasing the airborne weapons available to the shooter. This system is capable of wingman UAS could also be a "large" UAS that acts as a cargo train or refueling asset. [20]

The unmanned systems integrated roadmap by United States Department of Defense provided a quick summary of Manned Unmanned Teaming (MUM) [2].

> MUM teaming refers to the relationships established between manned and unmanned systems personnel prosecuting a common mission as an integrated team. More specifically, MUM teaming is the overarching term used to describe platform interoperability and shared asset control to achieve a common operational mission objective. This term also includes concepts of "loyal wingman" for air combat missions and segments of missions such as MUM air refuelling. This capability is especially vital for missions such as target cueing and handoff between manned and unmanned systems, where the operators not only require direct voice communications between the participants, but also a high degree of geospatial fidelity to accurately depict each team member's location with regard to the object being monitored. [2]
>
> MUM teaming was first employed in the late 1960s when the USAF flew AQM-34 equipped with Maverick missiles from airborne C-130 aircraft. Over the intervening years, other experimental UAS were flown from manned aircraft and during the Predator ACTD from a submarine. In 2002, the USAF demonstrated the ability to fly the MQ-1 from a flying C-130 also equipped with a FMV camera to prove a rapid, small-footprint deployment capability, and the ability to cooperatively prosecute targets with onboard and offboard systems. The Army also conducted MUM demonstrations beginning with the Airborne Manned/Unmanned Systems Technology (AMUST) Demonstration in 2001 with a follow-on Hunter Standoff Killer Team (HSKT) ACTD in 2006. During that demonstration, an AH-64D executed level of interoperability (LOI) 4 control of a RQ-5B Hunter UAS during a live fire exercise where Apaches lased for their own Hellfire missiles with the Hunter payload.[60] At these demonstrations, the Army Aviation Applied Technology Directorate successfully integrated a

> Mobile Commander's Associate[61], including UAS control, Link 16, and other various data links, into an Army airborne C2 system. This integration enabled an airborne C2 system operator located in a UH-60 Black Hawk helicopter to control a Hunter UAS and its sensor, for the first time, as well as send and receive tactical information in flight between strike aircraft such as the FA-18, and reconnaissance aircraft such as JSTARS. [2]

Although the above discussion focused on MUM, there is no reason to doubt its relevance to an eventual unmanned unmanned teaming, especially when UAVs eventually evolve to having the functional capabilities to match that of manned aircraft.

IV. ANALYSIS ON FACTORS DRIVING THE NEED AND THE OBSTACLES TO BE OVERCOME

A. FACTORS DRIVING THE NEEDS

1. Urban Operations

Operating in urban environments offers a number of unique challenges.

> Urban areas are conventionally viewed as a type of physical environment—essentially as complex terrain—which obviously they are. In this respect, urban areas are terrain complexes in which manmade constructions and a density of civil population are dominant features…From the U.S. perspective, urban terrain tends to restrict operations by counteracting most technological advantages in range, mobility, lethality, precision, sensing and communications. [65]

The dense populations inherent to urban areas require that joint force commanders pay greater attention to the relationship between civilians and military operations than in any other types of operations [66]. The urban environment includes challenges such as combatant identification, propensity for collateral damage, preservation of infrastructure, restrictive rules of engagement, line of sight obstructions (to include targeting and communications), and freedom of maneuver [66].

The urban terrain differs from one urban environment to another. An urban environment is not only characterized by the attributes of permanent features such as height and separation of buildings and street width, it is also a dynamic environment. The dynamic nature of the urban environment can be summarized by a quote from an IEEE proceedings document, "Network-Centric Systems for Military Operations in Urban Terrain: The Role of UAVs:"

> Small buildings arise in a matter of weeks, and large buildings in months. Buildings that are rubbleized by bombs become impassible obstructions that do not appear on anybody's map. Parked or abandoned vehicles and obstacles as simple as scrap metal can be effective blockages [48]

The complex physical terrain inhibits the performance of some technologies supporting command and control, including Line of Sight (LOS) communications and overhead surveillance [66].

> Man-made terrain in urban areas degrades communications capabilities, particularly line of sight, over-the-horizon, long-haul, and air-to-ground capabilities….Terrain in urban environments can impede a land force's ability to send and receive data directly to satellites. This can impact global positioning system receivers and inhibit their ability to provide accurate data. [66]

Effective command and control in the urban environment requires the ability to rapidly collect and disseminate information. Knowledge is a perishable asset; speed and precision are necessary to get the right information in the right hands as expediently as possible [66].

The UAV offers an affordable solution to address some of the challenges identified for operations in the urban environment. Potential applications include using a UAV as a communication relay node to bridge communication and using multiple UAVs to overcome LOS challenges for the purposes of tracking a moving target.

2. Communications Support

Communication is an important aspect of military operations. Current emphasis on Network Centric Warfare (NCW) and Information Superiority without a doubt places a huge demand on connectivity and communication. UAVs are viewed as a means to meet constantly increasing communication needs.

Quoting the UAS roadmap from the United States Office of Secretary of Defense (OSD), the major conclusions from a study conducted in 1997 on using UAVs as an Airborne Communication Node are [43]:

- Tactical communications needs can be met much more responsively and effectively with ACNs than with satellites.
- ACNs can effectively augment theater satellite capabilities by addressing the deficiencies in capacity and connectivity.
- Satellites are better suited than UA for meeting high capacity, worldwide communications needs.

The importance of timely information is mentioned previously in section 1 discussing the factors driving the need for multi-UAVs in urban operations, and the importance of timely information is definitely not unique to the context of Urban

Operations. In their thesis, NPS students Kent A. Landreth and John C. Glass describe the Tactical Horizon Extension Project, tested through the USSOCOM-NPS Cooperative Field Experimentation Program, and the importance of timely information. The importance is emphasized via a reference to the conduct of the Son Tay raid during the Vietnam War [67]. In fact the importance of timely information and the relevance to a wide-spectrum of military operations is obvious and does not require further quotes to substantiate the claim.

In Chapter II, we noted that the U.S. Army roadmap mentioned Reconnaissance and Surveillance as the number one combatant commander priority for unmanned systems. Landreth and Glass mentioned that Full Motion Video (FMV) is "king" at the tactical level of operations.

> At the tactical level of operations, FMV is king. It is the most desired medium through which decision makers can develop and assess a target or situation for action. FMV is real-time and requires little or no interpretation by a trained imagery analyst. It is essentially television. Virtually even asset which can provide FMV or even near-real-time imagery over the horizon or Beyond-Line-of-Sight (BLOS) falls into the category of Low Density High Demand (LD/HD) systems. [61]

FMV is one of the many products of Reconnaissance and Surveillance activities that can be conducted by a UAS. The use of other UAVs to provide connectivity is one of the means to allow timely delivery of these high value products to desired destinations. In addition, connectivity is also an enabling factor for command and control.

The UAS roadmap from the OSD anticipated that communication will need to exist in a multi-tier structure and provide a quick overview of the high level requirements [43].

> It is anticipated that communication relays will need to exist in a multi-tiered structure. For example, to create a wide communications footprint, the UA platform must have a capability of extremely long endurance, high altitude, and generate adequate power. It would provide an airborne augmentation to current tactical and operational beyond line-of-sight and line-of-sight retransmission capability. A more focused footprint to support brigade and below combat elements will require tactical communication relays to address urban canyon and complex terrain environment. Support of the communications relay mission will require continuous coverage in a 24 hour period, and sufficient redundancy to

meet "assured connectivity" requirements. Additionally, UA must be capable of relaying VHF-AM radio voice communications using an International Civil Aviation Organization (ICAO) standard and recommended procedures (SARPs) compliant radio operating with 8.33 kHz channel spacing from the ground station to the airspace controller communication. [43]

3. Collaborative Sensing

Collaborative Sensing tries to minimize the time taken to search a given area through a means of divide and conquer. In a single UAV search situation, one factor that affects the time taken to complete coverage of a given area is the field of view projection on the ground at which the search is conducted. At a given level of zoom, the altitude at which an aircraft flies determines the corresponding field of view projection on the ground. However, quality image and video resolution varies inversely with altitude; for a given payload zoom level, the quality of the resolution reduces with an increase in the height at which the payload is placed.

The use multiple UAVs allows greater area (number of UAVs multiplied by the area of the FOV ground projection) to be covered at a given time instance. The concept using of higher altitude UAVs to provide search cues for lower altitude UAVs tries to capitalize on the speed of a 'quick scan' using a bigger field of view and complements the loss of resolution with "close-in verification" of suspicion.

4. Swarm

The UAV Swarm has the potential to bring a wide range of benefits. One driving factor for operating UAVs in swarms is to reduce the manpower and logistics required to operate multiple UAVs. The ability to operate multiple UAVs in a collaborative manner to fulfill the same complex mission offers opportunity to increase efficiency (e.g., time spent) on tasks such as Wide Area Search. In addition, a UAV swarm has the potential to offer unique capabilities that cannot be fulfilled by any system operating only a single UAV. Creative ways that UAV swarms can be used includes acting as a decoy against radars and attacking high value targets by overwhelming their air defense.

One characteristic which allows the UAV swarm to be an attractive solution for creative applications is cost. Small UAVs are considered cheap relative to many other military systems. In fact, some small UAVs are marketed as dispensable. Operating multiple smaller UAVs also offers the potential advantage of operational flexibility and redundancy when compared to a single large UAV.

5. Loyal Wingman

Although the vision for the future is a multi-purpose, multi-mission capable UAV platform, there are definitely opportunities for a "loyal wingman" deployment concept due to physical and operational constraints.

Regardless of aircraft type, there exists a maximum payload capacity (size, weight, etc.) that the aircraft is designed to handle. This maximum capacity directly limits the amount of payload (sensors, weapon, fuel, etc.) that can be carried by the aircraft. In addition, the platform sensitivity to weight distribution also limits the amount of flexibility in changing configurations to tailor to specific situations.

A truly multi-purpose UAV will probably be very complex and, hence, costly. There is probably wisdom in not trying to place "all the eggs in one basket" where the loss of one platform can have a serious impact on operational capabilities. In addition, functional capabilities of an aircraft that are not used in its mission deployment carry an opportunity cost of not being able to deploy these functional capabilities elsewhere.

Operational constraints will probably limit the amount of functional capability that a single UAV platform can possess. Even after years of history in manned military aviation, there are still opportunities for manned aircraft to operate in a collaborative manner. Such opportunities also exist within the context of UASs. It is also reasonable to see a future "loyal wingman" concept come true for unmanned systems.

> The same technologies that keep UAS from any airborne collision will also enable UAS formation flight. Coordinated missions and cooperative target engagement will provide the same mission efficiencies as manned aircraft. [20]

B. TECHNOLOGICAL ENABLERS

The technology "round up" represents the toughest portion of our effort to gather the elements required to perform a holistic assessment of multi-UAV operations. The various roadmaps provided a good description for current (current with respect to the years of release of the roadmaps) technology, way of use, lessons learned, desired state for the future, research and development initiatives, etc. [1], [2], [20] and [43]. Typical domains described include, but are not limited to, the UAV platform, sensors technology, communication infrastructure, interoperability. This thesis will not attempt to repeat all the information in those roadmaps in this section but will highlight specifics deemed significant to the context of multi-UAVs. It is strongly recommended to refer directly to the original roadmap documents for a good general overview of current constraints and future needs.

Although UAS roadmaps generally provide sections summarizing the types of technology required or types being developed, the descriptions are usually not technically detailed enough to allow individuals concerned about implementing and integrating these technologies to develop an adequate understanding of how individual technological parts integrate together, much less conduct a proper assessment or study of emergence based on potential system of systems implementations. Information such as algorithms that are in study, the logistics/infrastructure that needs to be assumed, constraints and limitations of respective algorithms or underlying infrastructure that was assumed, pros and cons of respective implementations, etc., are spread across large volumes of technical papers across a huge spectrum of broad category technical domains and their respective sub-domains. Examples of these domains include communication, autonomous technology, sensor technology, human systems integration. In addition, within each domain, relevant information could be further spread across different perspectives such as study of relevant parameters (e.g., what are the measure of effectiveness and measure of performance, what are the factors affecting performance, etc.) for assessment, reliability studies, cost estimation, etc.

This section summarizes the references that were studied and the information directly obtained or derived after reading the references in the duration of the thesis. The information from this section is by no means all inclusive but is sufficient to present an individual looking into conducting assessment with the general direction for proceed and literature references to lead into further in-depth research.

1. Collision Avoidance

Collision avoidance is an important area of focus from the perspective of airspace integration. Integration of UAVs into civil airspace has been an area receiving significant attention. There is urgency to allow the UAS to make use of civil airspace for testing new systems and training UAS operators. The *United States DoD Unmanned Systems Integrated Roadmap* showed that the demand for airspace to test new systems and train UAS operators has quickly exceeded the current airspace available for military operations [2]. The same roadmap also showed many of the projected DoD UAS locations (up to year 2017) are without access to airspace compatible for military operations under the current (2011) regulatory environment [2].

The U.S. Air Force UAS Flight Plan revealed that the current (2009) combat airspace procedures for UAS were developed for uncontested airspace, which provides justification for an urgent need for technologies that allow UAS to access the civil airspace. The plan also provides brief insights into the amount of regulations to overcome [20].

> Current combat airspace procedures for UAS were developed for uncontested airspace. Our forces can dictate deconfliction procedures and create segregation airspace for operations at will. This cannot be taken for granted since host nations in theater may have restrictions on UAS operations that reduce their effectiveness. They could be limited by the same type of approval and procedures as they face in the NAS or under current International Civil Aviation Administration Organization (ICAO) rules. The issue of clearance to launch UAS sorties when well outside the combat zone is related also. The combat urgency of the CCDR will not necessarily be shared by the host nation outside the combat zone, resulting in approvals for flight not being expedited. UAS support to combat may be thwarted by lack of airspace integration capability. [20]

The most recent document found that come across that gives a comprehensive overview of the topic of airspace integration is NextGen Unmanned Aircraft Systems

Research's *Development and Demonstration Roadmap* (NextGen UAS R&D Roadmap), which documents the plans for responsive, efficient, timely, coordinated multiagency Research and Development efforts that will enable the U.S. to realize fully the benefits of UAS in the National Airspace System (NAS) [68]. A European effort that was presented at the UV Europe 2011 Conference was the MIDCAS project by Jens Fehler, Principal UAV Officer, European Defence Agency [4]. MIDCAS, a project signed during Le Bourget Air Show in June 2009, is the biggest project funded by the European Defense Agency, supported by the Ministries of Defense from five European countries and led by a consortium including 13 European companies that hold a large portion of European knowledge on Sense & Avoid as well as other technologies relevant to the project [69]. The mission of MIDCAS is to demonstrate the baseline of solutions for the UAS Mid-air Collision Avoidance Function (including separation), acceptable to the manned aviation community and compatible with UAS operations in non-segregated airspace by 2015 [4].

Although multi-UAV operations do not directly rely on successful integration into NAS or other civil airspace in general, there are merits to pay attention to and developments relating to airspace integration because:

- Collision avoidance, a major concern for airspace integration, is also a fundamental enabling requirement for collaborative scenarios that requires UAVs to operate in close proximity to other UAVs, other aircraft or even in dynamic environments with abundant structural obstacles (e.g., urban environment).
- Lessons learned from integrating UAS into civil airspace (e.g., the equipment and infrastructure required) may have relevance for an attempt to operate UAS with other military aviation assets.
- Successful integration or even major progression could have significant impact on the general public perception and acceptance regarding the ability of a UAS to operate safely and freely in an environment with other air traffic.

"Sense and avoid (SAA)" is described as an alternative means to meet FAA regulations to "see and avoid" [1]. The U.S. Army UAS Roadmap mentioned two approaches to address this functional need are ground-based sense and avoid (GBSAA) radar where the Army is the lead service and the airborne sense and avoid (ABSAA) radar where the Air Force is the lead service [1]. The Army's GBSAA plan is to develop a near-term solution called zero conflict airspace (ZCA), followed by a near-to-mid-term effort that is self-separation [1]. The same roadmap divided possible technical approach into passive or active techniques and subdivided into cooperative and non-cooperative traffic environments [1]. The active cooperative scenario involves detection through means of using interrogator and transponder, the active non-cooperative scenario relies on radar to scan the desired sector, passive cooperative scenario relies on all aircraft carrying a transponder than broadcast relevant information and the passive non-cooperative scenario relies on sensor (e.g., EO/IR camera) to detect traffic.

a. Automatic Dependent Surveillance – Broadcast (ADS-B)

The ADS-B corresponds to the passive cooperative scenario. The ADS-B (Figure 7) is a Global Navigation Satellite Systems reliant solution that allows desired parties (e.g., Air Traffic Control centers, pilots of aircraft, etc.) to observe the air traffic within the airspace. Each aircraft equipped with ADS-B OUT broadcasts its position and other data (e.g., flight number, airspeed, altitude and whether the aircraft is turning, climbing, or descending) via a wireless communication link. ADS-B equipment broadcasts multiple times per second at 978 MHz or 1090 MHz. Ground stations and other aircraft (equipped with ADS-B IN) within 150 miles receive the broadcast information. Air traffic control centers receive the information relayed via the ground stations. Air traffic information received is visually presented to human operators (e.g., air traffic controllers, pilots of aircrafts, etc.).

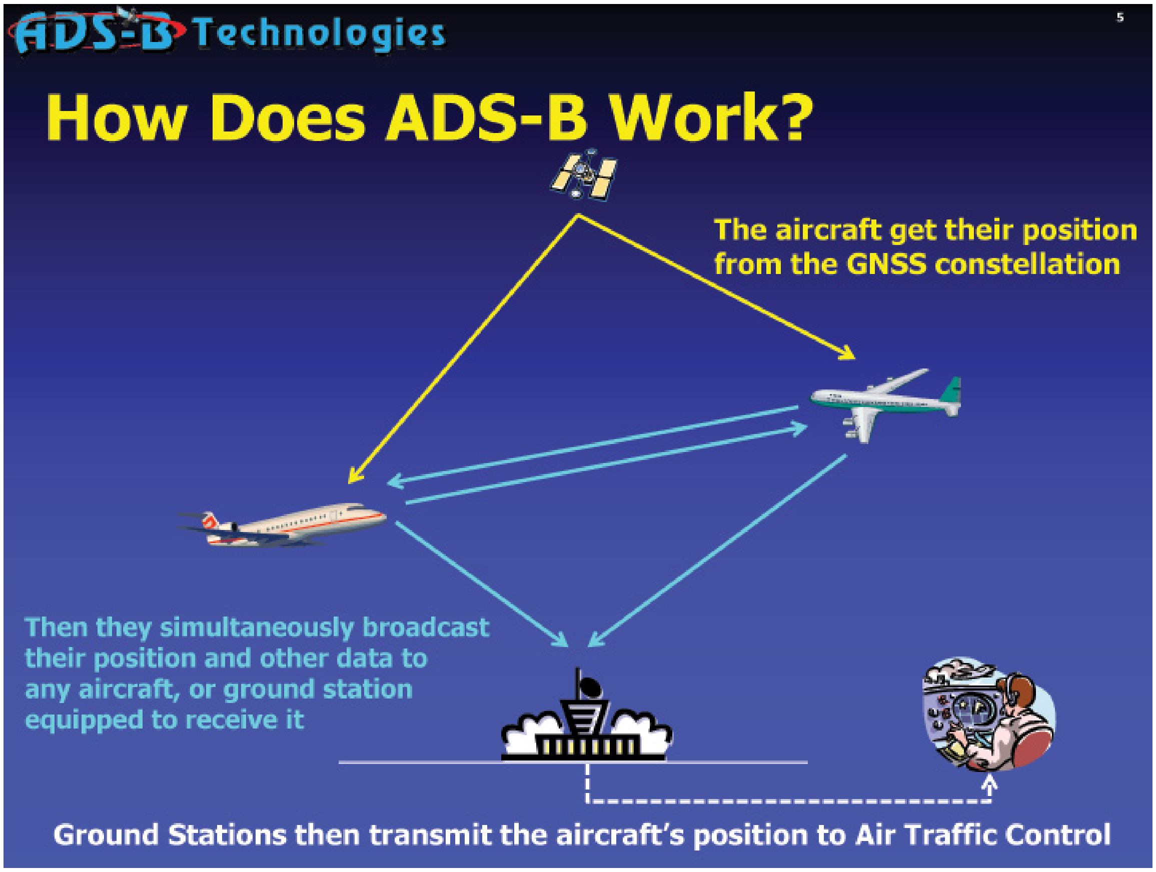

Figure 7. ADS-B Operational View. From [70].

b. *Due Regard Radar (DRR)*

DRR corresponds to active non-cooperative scenario. The U.S. DoD is funding the development of an affordable common, autonomous ABSAA system for the Airforce RQ-4B Global Hawk and Navy Triton (formerly known as BAMS) [68]. General Atomics Aeronautical Systems, Inc. (GA-ASI) has a prototype DDR which is being matured [71].

c. *Visual Detection*

Visual detection corresponds to a passive non-cooperative scenario. It is probably the closest to the "See" of the "See and Avoid" method of collision avoidance for manned aircrafts. Visual detection can be performed through the use of EO/IR cameras to search the surroundings for awareness of other aircraft.

2. GPS Denied Navigation

GPS denied navigation is a valid consideration in the urban environment where environment and other factors interfere with the GPS signals, resulting in a GPS denied environment. Intentional jamming is another valid scenario for considering GPS denied navigation. Feng Lin et al. [13] provided a good overview of alternatives to navigation methods in the absence of GPS.

> Due to the size and price limitation, light-weight and low-cost inertial measurement units (IMUs) are widely adopted for navigation of small-scale UAVs. Low-costs IMUs are characterized by high measurement noises and large measurement biases. Hence pure initial navigation using low-cost IMUs drifts rapidly. In practice, inertial navigation usually is aided by the global positioning system (GPS) to realize drift-free state estimation…Computer vision techniques have been successfully applied to various UAV navigation tasks. These navigation tasks can be generally divided into two categories according to whether prior knowledge of the environment is available or not. In the first category, certain prior knowledge of the environment is available. For example, an artificial landmark with known structure is placed in the environment. An onboard camera can take images of the landmark during flight. By matching the images with the real landmark structure, the pose (position and altitude) of the UAV relative to the landmark can be estimated…Another typical task in the first category is the map-based navigation. By using image registration techniques, the absolute UAV position can be estimated from geo-referenced aerial or satellite images. In the first category, the UAV states (position, velocity and altitude) can be estimated without drift. In the second category the environment is unknown….Two types of approaches are predominant in UAV navigation in unknown environments: (i) visual odometry (VO), and (ii) simultaneous localization and mapping (SLAM)….VO can estimate the UAV states with respect to the initial states by accumulating inter-frame motion information. Due to the error of inter-frame motion estimation, the state estimation given by VO drifts over time. As a comparison, SLAM not only estimates the UAV states, but also simultaneously builds up a map of the environment. In SLAM, past visual measurements are stored in the map and consequently used for refining current state estimation. So SLAM potentially can give more precise state estimation than VO….SLAM requires large computational and storage resources to maintain a large-scale map. By trading off navigation performance and resources required, VO is a more practical navigation approach than SLAM especially for the tasks where mapping is unnecessary. [13]

The same article by Feng Lin et al. [13] went further to provide an in depth discussion of their work and a quick comparison with existing work on vision-based navigation using homography. This thesis will not attempt to summarize that portion of the description and will instead recommend direct reference to the original article.

3. Autonomy

DoD's Unmanned Systems Integrated Roadmap cited "Technology Horizons," a 2010 U.S Air Force study that mentions the potential for increased autonomy to improve effectiveness through reduced decision cycle time, manpower efficiencies and cost reductions [2]. Figure 8 shows the DoD autonomy roadmap for unmanned systems.

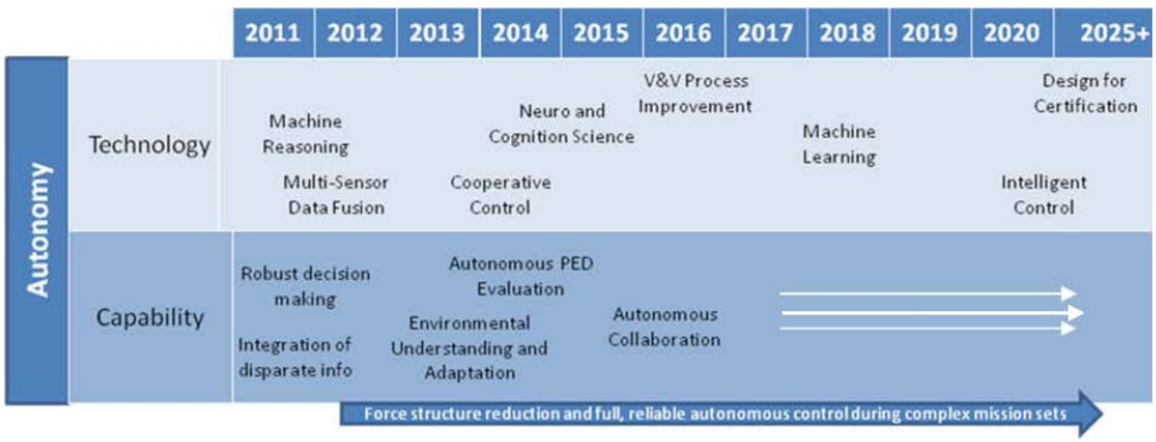

Figure 8. Autonomy Roadmap. From [2].

A key driver for autonomy is a desire to capitalize on the benefits of reduced manpower required to operate a UAS, reducing human operators to supervisory positions and increasing their span of control [43]. In the context of multi-UAVs, especially in swarm scenario, the application of autonomy to allow a small number of operators or even one operator to operate the entire swarm is the foundation which makes the concept feasible. Understandably, a majority of the papers describing UAV autonomy are discussions related to UAV swarm. The "Mini, Micro, and Swarming Unmanned Aerial Vehicles: A Baseline Study" report by the Library of Congress [61] is a useful reference which discusses some of the research being done and provides references to the related technical papers.

a. Collision-free Path Generation

Path generation can be centralized or de-centralized. A centralized approach is criticized for significant communication overhead and over reliance on a central decision maker and is hence susceptible to failure [8]. An argument to support the de-centralized approach is a perceived increase in robustness; a disadvantage is its sensitivity to information discrepancies across the UAV team [8]. Kevin et al. [9] demonstrated collision-free multi-UAV optimal path planning and cooperative control based on pseudospectral methods. The modeling approach used lends itself well to an architecture involving an offboard computational engine responsible for supervising the UAV operations [9] (centralized). David et al. [25] presented a hierarchical system for swarming where an initial globally optimal path is generated offline and trajectory replanner based on model predictive algorithms. Luca et al. [8] presented an extension to the Consensus Based Bundle Algorithm (CBBA) for task assignment to handle collision avoidance (and noise churning). Assigned tasks were checked for collision, and corrections were made through adding intermediate waypoints for obstacle avoidance after solving the shortest path problem using Dijkstra's algorithm. In the thesis of Chua Chee Nam [23], a direct method in exploiting the inverse dynamics of a vehicle in the virtual domain is used. In the context of collaborative search and coverage and collaborative sensing, a Bayesian update method approach can be used to dynamically determine search paths.

b. Task Assignment

Task assignment can be centralized or de-centralized. An article by Hyunjin Choi et al. [10] mentioned a few approaches to handle task assignment and provided a brief overview of the advantages and disadvantages.

> Task assignment has been regarded as a combinatorial optimization problem in which combinations between UAVs and various tasks must be deciphered. Examples of combinatorial optimization problems include the traveling sales problem or the vehicle routing problem. Finding exact solutions are very difficult because combinatorial optimization problems possess non-deterministic polynomial time, which results in computational complexity. Two approaches have been developed to overcome this

> complexity. One approach is mathematical programming approach such as mixed integer linear programming. The second approach is a meta-heuristic algorithm such as the genetic algorithm and particle swarm optimization. Mathematical programming approaches often provide solutions that are better in quality than solutions derived from meta-heuristic algorithms, but mathematical programming usually requires much more computation time than its counterpart. Conversely, the meta-heuristic approach obtains solutions quickly, however the quality of the solution may be poor. [10]

CBBA is another example of approach for task assignment. CBBA lends itself to the decentralized task assignment approach.

4. Communication Network

a. Communication Infrastructure

Previous sections discussed the importance of the UAS role in ISR and the importance of timely information. The communication infrastructure is the foundation that will allow the right information to get in the right hands as expediently as possible. Lieutenant Colonel Duane T. Carney (2008) mentioned in his strategy research project that the UAS requires network resources to operate in order to realize their maximum potential, and DoD cannot progress on the path to implement its vision to Network Centric Warfare without fully integrating the UAS into the theater communications network [72]. The maturity of the communication infrastructure directly affects the value of UASs.

The OSD and U.S. Air Force roadmaps mentioned the need to connect the UAS to the Global Information Grid (GIG) [20] and [43]. According to the United States National Security Agency website, GIG is the globally interconnected, end-to-end set of information capabilities for collecting, processing, storing, disseminating and managing information on demand to warfighters, policy makers and support personnel [73]. Understandably the technical details and status of integration was not readily available in public literature.

A multi-UAV system (including consideration for cooperation with manned elements or other unmanned systems) will likely require even greater emphasis to be placed on the communication infrastructure. A deployed system or system of systems will likely require network interoperability between the elements instead of traditional dedicated point-to-point communication between respective UAVs and the control stations. The United States Army Future Combat System (FCS) is a significant effort of reference to integrate UAVs with other elements into a complete System of Systems. FCS was originally planned to consist of 18 systems linked by an advanced information network but was later reduced to 14, consisting of eight new types of ground vehicles, two classes of UAV, several unmanned ground vehicle and an attack missile (Figure 9) [6]. Although eventually halted in 2009[9] [5], the FCS offered a good case study for technological maturity assessment and lessons learned (both in terms of acquisition and technical insights). Research into the Joint Tactical Radio System (JTRS) and the Warfighter Information Network – Tactical (WIN-T) [6], two critical elements of the FCS, will probably also be meaningful.

[9] Succeeded by Army Brigade Combat Team Modernization (ABCTM) program.

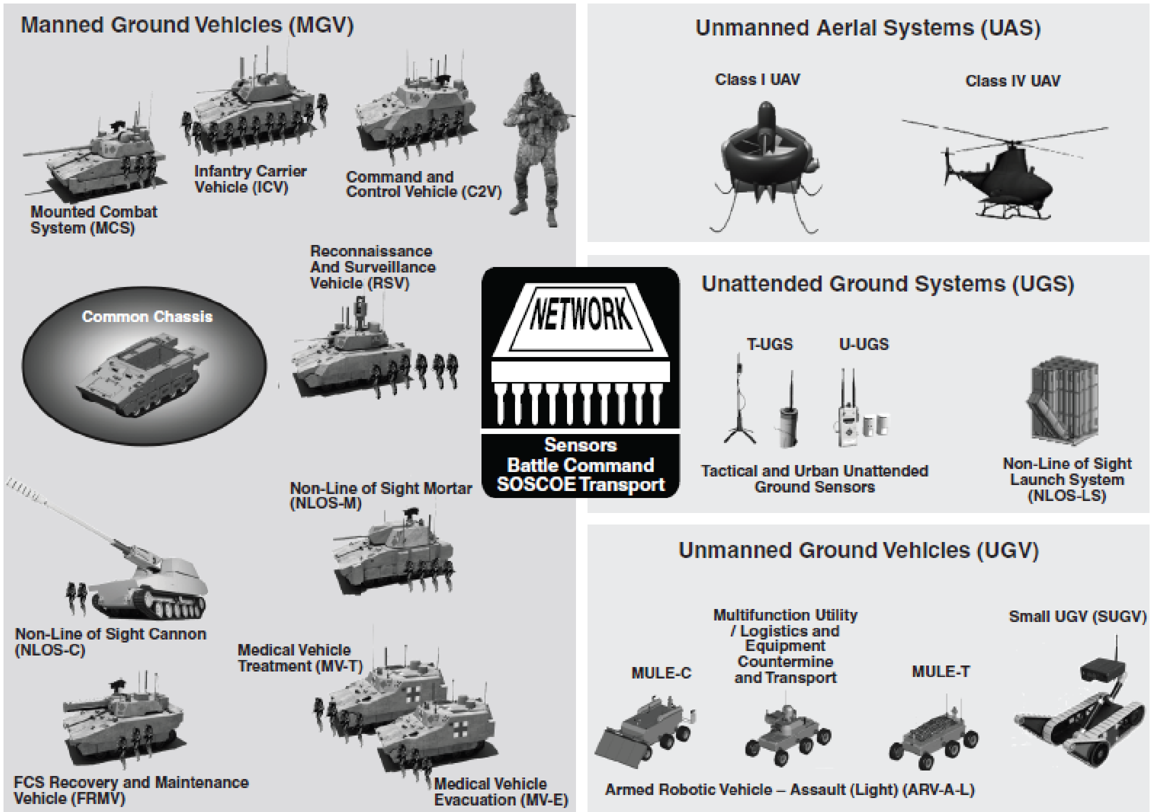

Figure 9. United States Army Future Combat System (14 systems). From [6].

In addition, paying attention to developments in the Distributed Common Ground System (DCGS) of the respective services may provide reference for the operational requirement, technical design and other information such as User Interface (UI) and lessons learned. Army Battle Command System (ABCS) and the United States Navy's Cooperative Engagement Capability (CEC) are examples of other systems for reference and study. Examples of references for CEC are an article from Johns Hopkins Applied Physics Laboratory [74] and a case study report by National Defense University [75].

b. Spectrum and Bandwidth

Frequency and bandwidth are traditional challenges for UAS operations. Examples of operational issues from the Global War on Terror relating to frequency spectrum and bandwidth that are mentioned in the OSD UAS roadmap [43] include:

- Despite having the capability to operate multiple UAs per system simultaneously, the limited number of frequencies available often restricted the number to one UA airborne at a time.
- Frequency interference (loss of UA link) was more often from friendly than hostile.
- Urban combat is hostile to high bandwidth wireless data communications and can result in loss of connectivity even at short distances.

Cognitive Radio (CR) and Dynamic Spectrum Access (DSA) techniques may offer potential solution to frequency congestion problem. DSA is mentioned in the DoD Unmanned Systems Integration Roadmap, although the same document also mentioned that a study by the United States Air Force Scientific Advisory Board evaluated DSA as far from being a proven technology [2]. An article by authors from the University of Pittsburgh mentioned that although a large volume of research has been conducted on the area of CR in the last decade, the deployment of a commercial CR network has yet to emerge; the paper also discussed some challenges in the real world scenarios that were not included in research literature [76].

A collaborative environment will further stress bandwidth requirements, adding overhead for collaborative communication on top of the need to communicate sensor products and ISR information. In addition to the bandwidth capacity of dedicated equipment for point-to-point communication between the UAVs and between the UAV and other collaborative elements, the bandwidth capacity of equipment to extend the range (such as commercial satellites) should also be considered and assessed. In addition, the cost associated with the use of commercial satellites is potentially significant and should also be a factor considered during design and assessment. Issues regarding satellite communication (SATCOM), spectrum management and bandwidth management are discussed in the United States Air Force UAS Flight Plan [20].

> Commercial SATCOM: While today's UAS almost exclusive use commercial SATCOM, it has some major drawbacks. First and foremost, commercial SATCOM is an open commodity where the DoD competes with numerous other communications users (i.e., TV, international telephone, data, and facsimile). Also, commercial SATCOM transponders are sized for the community they intend to support which ranges typically from 36–54MHz. While that transponder size is sufficient for

> Predator/Reaper it is less than adequate to support Global Hawk's Block 20/30/40 full throughput needs. Finally, while figures vary with each lease, commercial SATCOM bandwidth typically costs approximately $40K per MHz per year. If 50 Predator/Reaper caps remained on commercial SATCOM, the annual recurring cost would be approximately $25M assuming an individual cap data growth to 12.8 Mbps. [20]

Compression offers a means to reduce bandwidth requirement. The video quality required for unmanned systems would nominally be levels 4M/4H and 3M/3H of the motion imagery systems matrix (MISM[10]) [2]. Bandwidth limit potentially is a major constraint when selecting the architecture/design/algorithm for a collaborative system.

5. Interoperability

Traditionally UASs are acquired and operated largely as an "isolated system" by respective services [31]. These systems therefore are not designed for interoperability. The following statement from the DoD Unmanned Systems Integration Roadmap, regarding collaborative autonomy, captures the importance of interoperability for unmanned systems.

> The collaborative autonomy that is developed must be scalable to both larger numbers of heterogeneous systems as well as increased mission and environment complexity. Collaborative autonomy must be able to adapt to the air, ground, and maritime traffic environment and to changes in team members, operators, and the operational environment. [2]

The vision for the future collaborative environment involves flexibility to quickly put together teams to meet different operational needs. This requires the ability to work with other systems – interoperability to be engineered into the systems. The tenets of common definitions for plug-and-play interoperability are systems functionality descriptions and architectures, messaging standards (e.g., STANAG 4586, JUAS, USMTF) [2]. The same roadmap advocates overarching principle involving open architecture (OA) and service-oriented architecture (SOA) to facilitate interoperability. The section describing and justifying the approach is cited in this section.

[10] See Motion Imagery Standards Profile (MISP) Recommended Practice 9720d, MISM, Standard Definition Motion Imagery

> OA utilizes a common set of interfaces and services; associated data models; robust, standard data busses; and methods for sharing information to facilitate development. OA involves the use of COTS components with published, standard interfaces, where feasible, at all levels of system design. This approach avoids proprietary, stove-piped solutions that are vendor-specific and enables innovation to be better captured and integrated into systems design. The OA approach allows for expanded market opportunities, simplified testing and integration, and enhanced reusability throughout the program life cycle. The Navy's Cruiser Modernization Program is one such effort.
>
> The OA process encourages innovation, allows information sharing among competitors, and rewards Government and industry for this collaboration. It allows programs to include small businesses in systems acquisition activities as a valuable, affordable, and innovative source of technologies and capabilities. The result is a better product.
>
> DoD unmanned systems consist of a wide range of programs, architectures, and acquisition approaches. To create a common framework for development and acquisition, DoD adopted principles of OA and service-oriented architecture (SOA). While the OA is the contracting, architecture, and business process methodology used to develop and acquire systems, a SOA is a specific way of designing software, in a standardized architecture, that uses interchangeable and interoperable software components called *services*. When coupled together, the result is a business approach to acquiring software developed within a common engineering construct that promotes reuse, cost reduction, competition, growth opportunity, expandability, innovation, and interoperability among similar systems.
>
> SOA provides a set of principles or governing concepts that are used during the phases of systems development and integration. This type of architecture attempts to package functionality as interoperable services within the context of the various business domains that use it. SOAs increase functionality by incorporating new services, which are developed separately but integrated within the system's common framework as a new capability. Their interfaces are independent of application behavior and business logic, and this independence makes the interfaces agile in supporting application changes and enables operations across heterogeneous software and hardware environments. [2]

Figure 10 shows the DoD interoperability roadmap for unmanned systems and Figure 11 shows the roadmap for manned unmanned teaming. The OSD UAS roadmap includes a discussion and list of standards for interoperability which are provided in Appendix E [43].

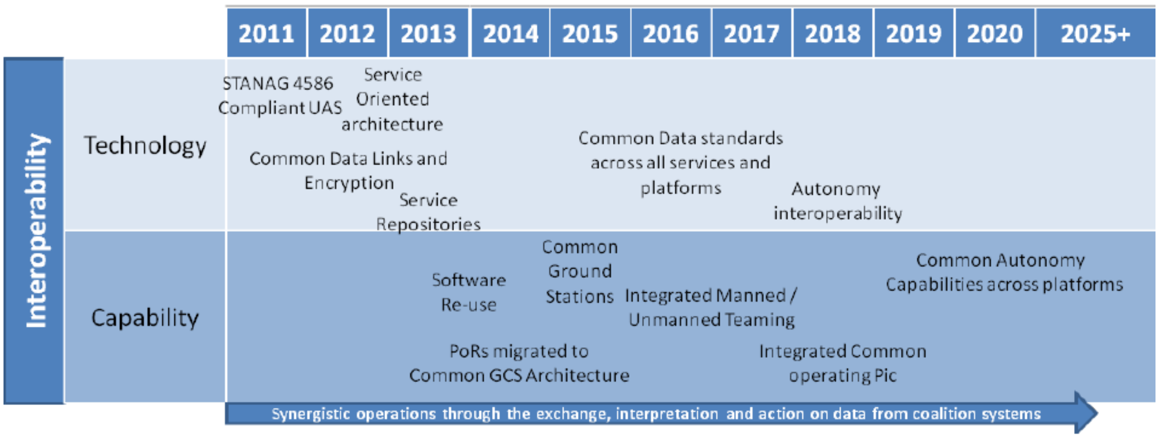

Figure 10. Interoperability Roadmap. From [2].

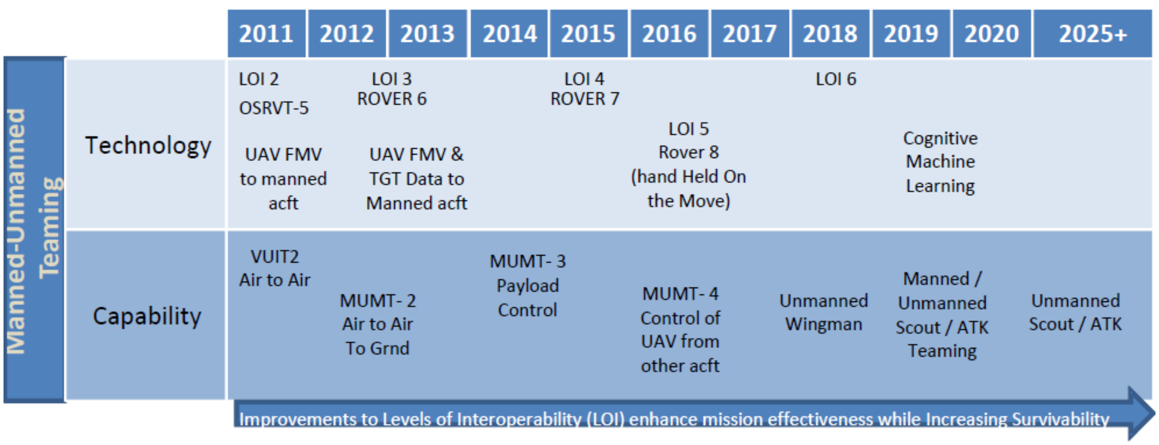

Figure 11. Interoperability (Manned Unmanned Teaming) Roadmap. From [2].

6. Power

Although not an area that was focused on for this thesis, no study regarding the effects of various collaborative algorithms/designs on endurance was found. A huge increase in communication requirements is likely to have significant impact on endurance. Power/endurance is a candidate area for close scrutiny when assessing any collaborative design that is proposed.

C. FACTORS TO CONSIDER DURING SYSTEM ENGINEERING ACTIVITIES

1. Technology

The technological assessment (2009) for the status of collision avoidance technology is summarized in the U.S Air Force UAS Flight Plan [20].

> See and avoid has not been defined in terms of minimum detection distance, minimum field of view, or minimum scanning rates/patterns. There are many variables that affect this analysis including pilot skill, pilot flight currency, density of traffic, and flight speeds. Further, the level of acceptable risks has not been defined. Additionally, there are no development standards for Sense and Avoid. Technological solutions are being matured in the labs, but have not been approved yet because the standards do not exist and the modeling and simulation to make the safety case is just beginning. [20]

From the near-term (2010) GBSAA goals [11] given in the U.S Army UAS Roadmap, the current state of technology for SAA seems far from matured. The information from the NextGen UAS Research, Development and Demonstration Roadmap [68] seems to support this assessment. The compliance date for all aircraft flying in United Sates class A, B and C airspace to carry ADS-B is set at 1 January 2020 [77]. GA-ASI announced the successful flight test of their DDR prototype on Predator B UAV in February 2013 [71] but technical details regarding the prototype system are not available for reference.

The DoD Unmanned Systems Integration Roadmap [2] describes the technical challenges for manned unmanned teaming. Although the statement was framed for the context of manned unmanned teaming in the maritime environment, the challenges described are nevertheless expected to be true even in the general context of collaborative missions.

> Some of these challenges are technical. They range from near-term issues such as the limited ability to integrate and deconflict various radio across a

[11] GBSAA near-term goals given as: a) develop, text, employ, and field ZCA – Zero Conflict Airspace b) develop initial SAA requirements and standards c) develop self-separation algorithms d) develop and test GBSAA self-separation capability e) expansion and definition of the USAIC sensor network f) initial integration work to integrate the capabilities of GBSAA and ABSAA g) initial semi-autonomous flight h) expand GBSAA to possible deployable system supporting disaster relief and theater combat roles.

> secure communications network… This ability requires a high degree of hardware and software interoperability, scalable autonomy, human system interfaces, new collaborative algorithms, and network mission tools. The platform must do significant levels of onboard processing to not only reduce bandwidth required, but also collaborate with other unmanned vehicles without operator input. [2]

In the context of autonomy, there is an abundance of papers regarding respective specialized areas and papers justifying the validity of various approaches and algorithms. However, the conduct of experiments and simulations considering the entirety of the context is important to prove the maturity and expose undiscovered technical challenges. For example a team of UAVs deployed for collaborative sensing will likely require auto separation, task assignment, path generation, obstacle sensing and avoidance. Environmental factors causing occlusion, range and endurance limits, communication overhead from collaborative communication, bandwidth limits, onboard processing capability, etc., are factors that constrain the design or limit the maximum number of UAV in a team, and these needs to be considered and assessed in entity. Unfortunately, papers describing studies of such a broad scope was not found.

Arguably the value of the UAS in its top priority role of C4ISR depends on the ability to deliver timely required information to the right places. In other words, the maturity of the communication infrastructure is the backbone for UAS and collaborative operations. The amount of information available regarding communication infrastructure is insufficient for a conclusive assessment, but the inference from the status of various programs referred to and the general tone of discussion regarding architecture and interoperability, is the infrastructure is not matured.

Although not the focus of our review of the literature, human factors related studies and results seem to be heavily lacking. Development of concepts for the human machine interface (HMI) and graphical user interface (GUI) and for assessment of these areas might be warranted.

Consolidating the impression from literature review into various areas of technological enablers, there is no conclusive evidence that technology to put together a deployable complex collaborative system or system of systems, with ambitious vision such as plug and play interoperability, is matured. The failure of the Army's Future Combat System and the criticism toward it may be a representative indication that the conditions are not ready for an ambitious complex system. Nevertheless are indicators that suggest that the design of a system or system of systems that has limited functionality and limited interoperability outside of the original design context is not very far from technologically feasible, if not already feasible. Technology for the respective domains seems relatively developed for assessment studies to begin. The value of a deployed collaborative system may not be just the operational value but also additional benefits such as accumulating confidence for eventual acceptance.

2. Concept of Operations (CONOPs)

Limited CONOPs description for multi-UAV context was found despite reading through various UAV related roadmaps found in the public domain. Several writers who follow military news and write about military applications [3] and [14], discuss interest (for example the U.S. Navy interest in Unmanned Carrier-launched airborne surveillance and strike) and capabilities for UAS, while there is an absence of published CONOPs from any military service in the public domain. Research papers were used as reference for possible applications. However, the scenarios may sometimes be limited in scope or does not adequately incorporate all real-life challenges associated with the scenario. The objective of identifying strongly supported[12] CONOPs was likely not met. The closest to a validated CONOP was a high level desire to network a UAS as one of the components in a collaborative information sharing environment for information dominance and a short discussion on manned unmanned teaming. The system or system of systems to meet this desire is probably the most complex. Arguably the limited scope scenarios present a high amount of risk for industry to focus time and effort to conduct comprehensive feasibility studies or determine detailed complete designs, and the high level desire is at too high a level of abstraction for any single organization or expert to conduct comprehensive feasibility studies. Strongly validated CONOPs/applications may have been kept away from the public domain because of security classification or the current state of progress had not reached the stage where system implementation level of details is available.

[12] The author defines strongly supported as either described in formal documents from operating/acquiring authorities or has been reasonably validated for feasibility.

In a typical systems engineering approach, analysis of stakeholder needs and operational requirements provides the foundation for downstream process and analysis. The presence of assessable CONOPs could arguably focus efforts for feasibility studies.

3. Human Factors / Regulations / Legal Restriction

Human resistance can play a significant role in hindering the deployment of UAS technologies. Example of evidence of human resistance to UAS or application of UAS for certain operational purpose is mentioned in *Navy launches unmanned aircraft from carrier for first time* [3] by Fox News, which cite concerns over the development of systems that could become weaponized and have less and less human control over launching attack. An informal discussion between the author and others within the UAV community, including individuals involved in managing UAS projects, revealed that convincing the relevant authorities on issues such as safety is a major hurdle regarding UAS use and exploration of new ideas regarding how the UAS could be deployed.

Two statements, relating to integrating the UAS into NAS, from the Air Force UAS Flight Plan [20] was interpreted as an illustration of human resistance as an obstacle for UAS development.

> A challenge to fully integrate UAS is NAS access. Over the years as manned aircraft operations increased, rules were developed to increase the safety of flight. The most basic method of deconfliction is to see and avoid other aircraft (14 CFR 91.113). This is assumed as the most basic universal means when all other procedures and equipment have not prevented a conflict situation. See and avoid also hold the pilot as the one ultimately responsible in any visual environment. This is a major consideration and therefore, this precedent that has served us well in the past, is not easily changed or replaced. [20]

> The sense and avoid technological solutions coupled with the DoD and FAA rulemaking can serve as a model for international airspace solutions. Part of the reason the FAA has delayed the development of rules and standards, is due to pressure from other NAS users. [20]

An article by Hoffman et al. [78] also expressed similar sentiments where cultural resistance at senior and midlevel leadership may become a cultural impediment to the UAV "revolution." A typical concern about UAS related operations is safety related concerns. Lacher et al. [79] discussed the possibility of operating small a UAS in non-navigable airspace (for manned aircraft) that poses an acceptable risk to both other aircraft and people on the ground. In the article, aviation risk is discussed using three major categories. The first category refers to death or injury of persons on board subject aircraft, resulting from a mishap. The second category refers to death or injury of persons on board another aircraft resulting from a mid-air or surface collision between two or more aircraft/ground vehicles. The last category refers to death or injury of persons on the ground (not in an aircraft or vehicle involved with a collision) resulting from a mishap or collision. Much work needs to be done convincing stakeholders such as regulators, military leaderships and the public about the safety aspects of UAS operations. Regulations and standards need to be revised to handle the UAS "revolution," as illustrated by the efforts to integrate UAS into NAS. In addition, legal and morals issues, some of which are discussed by Anderson [80], are additional constraints on UAS operations, and concrete guidelines need to be established.

Success stories such as successful integration of UAS into NAS could play a significant part in breaking down human resistance. Progressive evolution of deployed systems could potentially be another means. Conducting a comprehensive and meaningful system assessment, such as a safety related assessment, and the consolidation and availability of these results could probably encourage greater participation from a wider audience.

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V. SITUATIONAL AWARENESS FOR UAS

Situational awareness is essential to operate a UAV safely. Situational awareness generally refers to the understanding of what is happening in the vicinity and also making use of that information to anticipate what might happen next. In the context of UAV safety, situational awareness allows the pilot to decide on the best course of action and also to evaluate his options. In LOS operations, the pilot has visual awareness of both the UAV and the environment. In BLOS operations, which are typical for a large number of UAS applications, the pilot is deprived of the ability to directly see his aircraft or its surroundings. In such cases, there is a challenge regarding how to provide situational awareness to the pilot. While operating in the NAS or other commercial airspace, situational awareness can be in the form of air traffic advice from ATC components. Active methods, such as scanning the environment with onboard radar, offer another way to obtain information of the elements within the vicinity. Cooperative communication to update elements within the vicinity is another approach. The ADS-B implementation is an implementation of the cooperative communication approach. However, when operating in areas where ATC facilities are not available and transmission is not desirable, situational awareness through passive sensing (e.g., EO/IR cameras) becomes the only approach that remains feasible.

Later in this chapter we introduce some current cooperative and non-cooperative systems that can potentially be used for providing situational awareness in the context of UAV operation.

This section describes the author's experience handling ADS-B and EO/IR camera tracking systems with the intent to explore the concept of collision avoidance using visual detection.

A. SITUATIONAL AWARENESS

1. Situational Awareness with ADS-B

Figure 12 shows the context and the interaction between components for collision avoidance when ADS-B is used to enhanced situational awareness. The figure summarizes three levels of abstraction (ADS-B as a system, aircraft as a system and the full collision avoidance context involving multiple aircrafts) into one diagram (illustrated by the boundaries drawn). In one aircraft (right), the full details of components and their interactions with one another are shown. In the other aircraft (left), only details relevant to illustrate the interaction between aircrafts (for collision avoidance context level of abstraction) are shown, and duplicated details relevant only to within the boundary of the aircraft are intentionally omitted. The diagram is intended to illustrate the general context and does not include variations that need to be considered in more specific scenarios. For example, the operator/pilot is intentionally drawn within the boundary of the aircraft such that the diagram is relevant to both UAV and manned aircraft. In the context of UAV, the pilot will be situated remotely and connected by a communication link. This difference needs to be considered when dealing specifically with UAVs but is not explicitly shown in the diagram. Similarly, in the context of smaller UAVs and for swarm implementation, the desired implementation will likely be autonomous avoidance. This difference is also not explicitly illustrated in the diagram.

The context of ADS-B is described in Chapter IV. Within the context of a single aircraft, the pilot or an operator monitors the airspace situation display for potential collision threats and make counter measures (such as warning the pilot of the other aircraft of potential intrusion or maneuvers to prevent a potential collision). Advice from the ATC or advice from another pilot or operator is another avenue where the pilot or operator is made aware of a potential collision threat. Within the collision avoidance system of systems context, multiple aircraft exist and exhibit the same interactions concurrently with each other, ATC, ADS-B ground station and GPS satellites, as described in the context of a single aircraft.

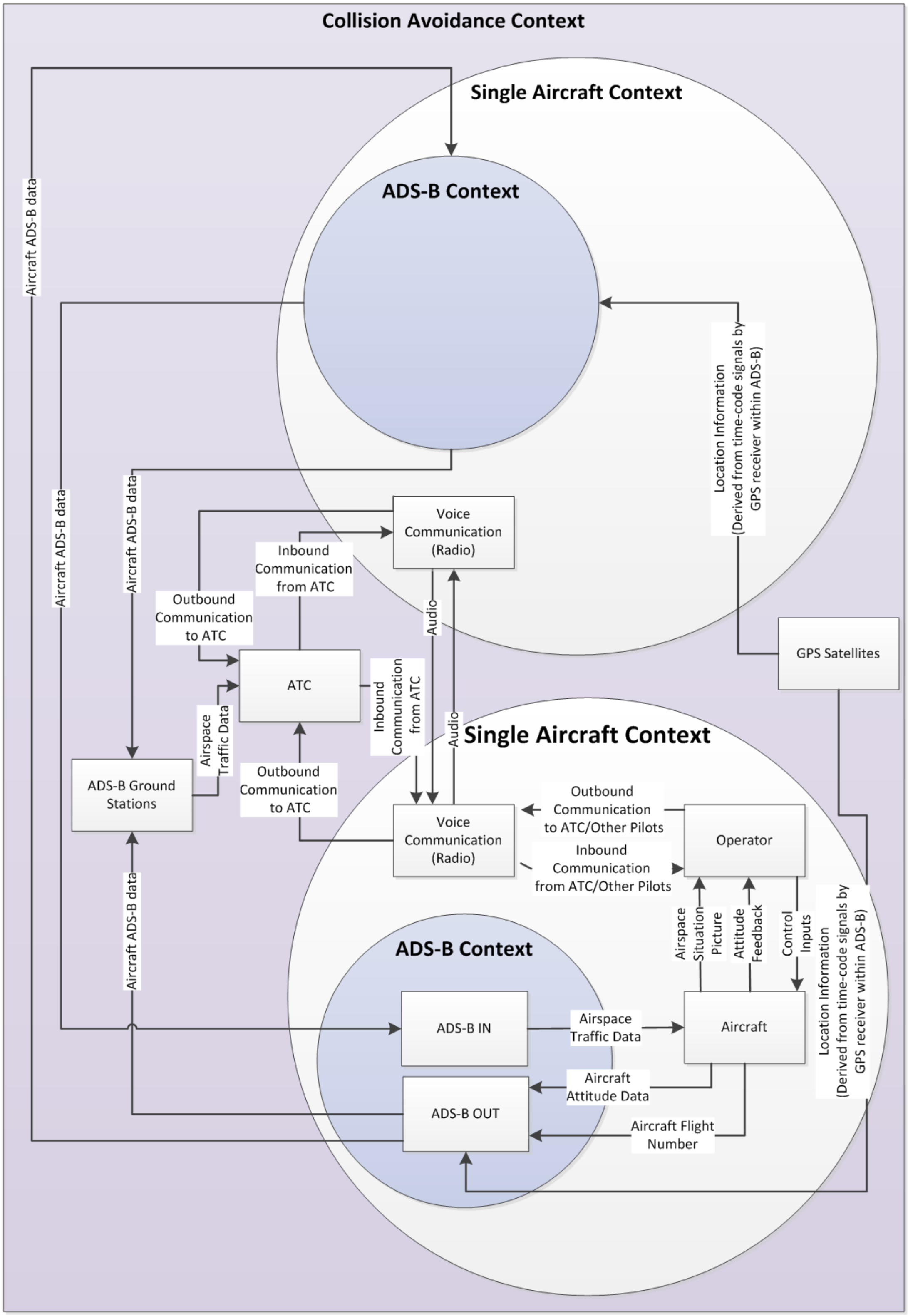

Figure 12. Context Diagram for Collision Avoidance with ADS-B

Index	Interface	Description
1	ADS-B IN with Aircraft	Information exchange. ADS-B IN sends received airspace traffic data (consolidated information received from each aircraft within the vicinity) to the aircraft.
2	ADS-B OUT with ADS-B Ground Stations	Information exchange. ADS-B OUT sends aircraft ADS-B data (consolidation of position and other aircraft data such as aircraft attitude and flight number) to the ADS-B Ground Stations by broadcast. Broadcast is sent in clear (not encrypted).
3	ADS-B OUT with ADS-IN	Information exchange. ADS-B OUT sends aircraft ADS-B data (consolidation of position and other aircraft data such as aircraft attitude and flight number) to the ADS-B IN of another aircraft in the vicinity by broadcast. Broadcast is sent in clear (not encrypted).
4	ADS-B OUT with Aircraft	Information exchange. ADS-B OUT obtains relevant aircraft information (e.g., Attitude data and flight number) from the aircraft.
5	ADS-B OUT with GPS Satellites	Information exchange. ADS-B OUT determines aircraft location information based on the GPS receiver (built-in) interaction with the GPS satellites network.
6	Aircraft with Operator/Pilot	Information exchange. The Operator provides control inputs to the aircraft via control interfaces. The aircraft provides attitude information feedback and display the Airspace Traffic Data received from the ADS-B IN as an Airspace Situation Picture to the Operator.
7	Operator with Voice Communication (Radio)	Information exchange. The Operator sends outbound audio messages to the ATC or other aircrafts via the radio. The Operator receives inbound audio messages from the ATC or other aircraft operators via the radio.
8	Voice Communication (Radio) with Voice Communication (Radio)	Energy exchange. The radio receives signal wave (encoded audio messages) transmitted by another radio.
9	Voice Communication (Radio) with ATC	Energy exchange. The radio receives signal wave (encoded audio messages) transmitted by ATC. The radio transmits encoded audio messages (signal wave) to the ATC.
10	ATC with ADS-B Ground Stations	Information exchange. ATC receives airspace traffic data (consolidated information received from each aircraft within the vicinity of the Ground Stations) from ADS-B Ground Stations.

Table 3. Interface Description for Collision Avoidance System of Systems context with ADS-B

2. Situational Awareness Supplement by Visual Detection

In this scenario, the change to the context described in Figure 12 is an additional visual input (via visual sensor output) to the pilot/operator.

B. SITUATIONAL AWARENESS COMPONENTS DESCRIPTION

This section contains a description of the following four systems that can be used to provide situational awareness:

- Appareo Stratus 2 ADS-B and ForeFlight Mobile
- Flightradar24
- PERCEPTIVU (PVU-Mariner and PVU-Tracker) and MOOG QuickSet GeminEye System
- SkyIMD SkyFusion Pak 2000

The first two systems of Appareo Stratus 2 ADS-B and Foreflight Mobile and Flightradar24 can be used for the cooperative implementation approach and the last two systems can be used for the non-cooperative approach.

1. Systems for Cooperative Approach

a. Appareo Stratus 2 ADS-B and ForeFlight Mobile

Appareo Stratus 2 (Figure 13) is an ADS-B receiver that is able to deliver subscription-free weather, ADS-B traffic, GPS position and attitude information to an iPad installed with ForeFlight Mobile application (Figure 14). ForeFlight Mobile provides the GUI that presents the received information and allows the user to choose the information to display. Appareo Stratus2 integrates exclusively with ForeFlight Mobile. Information exchange between Appareo Stratus 2 and ForeFlight Mobile is through a WiFi connection (between Stratus 2 and iPad). Table 4 summarizes the technical specifications for the Appareo Stratus 2.

Figure 13. Appareo Stratus 2 ADS-B receiver. From [81].

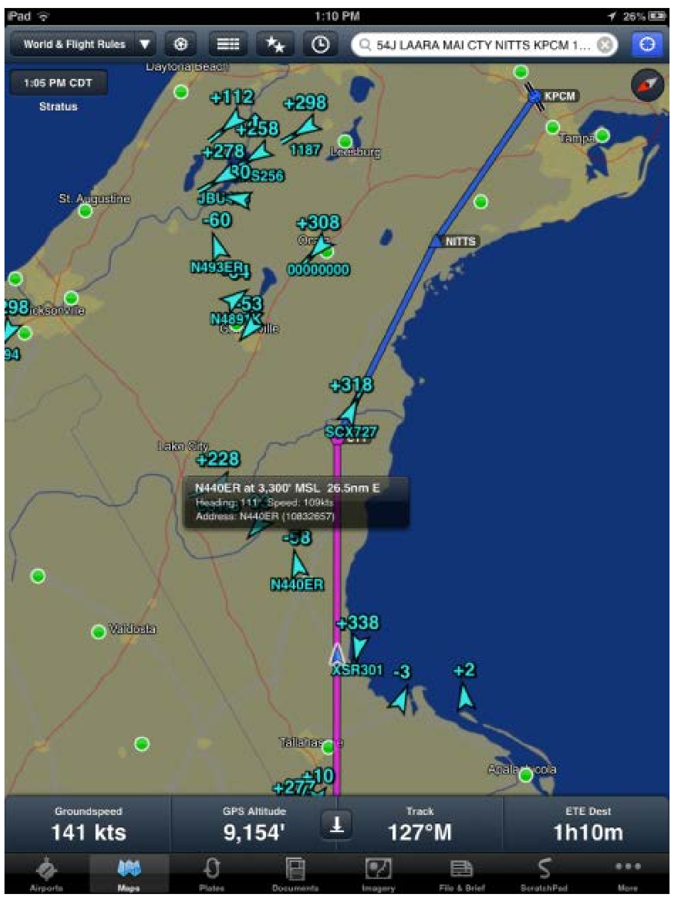

Figure 14. ForeFlight Mobile Application. From [82].

Index	Parameter	Specification
1	Dimensions	2.6” x 6” x 1.25” 9.7 oz.
2	Antenna	Internal antenna for wire-free operation in most cockpits
3	Cooling	White case and built-in fan
4	Battery Life	Battery life up to 8 hours and recharges via micro USB
5	GPS	Active WAAS GPS for improved position information and support for speeds up to 900 KTAS
6	ADS-B	Dual band ADS-B receiver (978 MHz and 1090 MHz). Receiving from ADS-B towers requires ADS-OUT in vicinity as most towers
7	AHRS	Stratus includes a complete Attitude Heading Reference System (AHRS) for supplemental attitude information in the cockpit
8	Miscellaneous	Tested to DO160F for magnetic effect and altitude, ESD via the 8kV Human Body Model, and vibration tested using 10–500–10Hz 1oct/min 1hr/axis (3 axis).

Table 4. Technical Data. After [82] and [81].

b. Flightradar24

Flightradar24 (Figure 15) is an application that shows live air traffic from around the world. The application is available for a number of different operating systems, including iOS for iPad and iPhone and android OS. The primary source of information is ADS-B. Aircraft positions are also calculated using the Time Difference of Arrival method of Multilateration for areas where the ADS-B coverage is good. Radar data from the Federal Aviation Administration (FAA) in the United States is another source of information. The information is delivered to the user over the Internet. FAA data are delayed (up to 5 minutes) and displayed in a different color (orange) [83]. Flightradar24 can be downloaded and installed from the application stores of the respective operating systems. Flightradar24 is available in licensed and free-to-use versions.

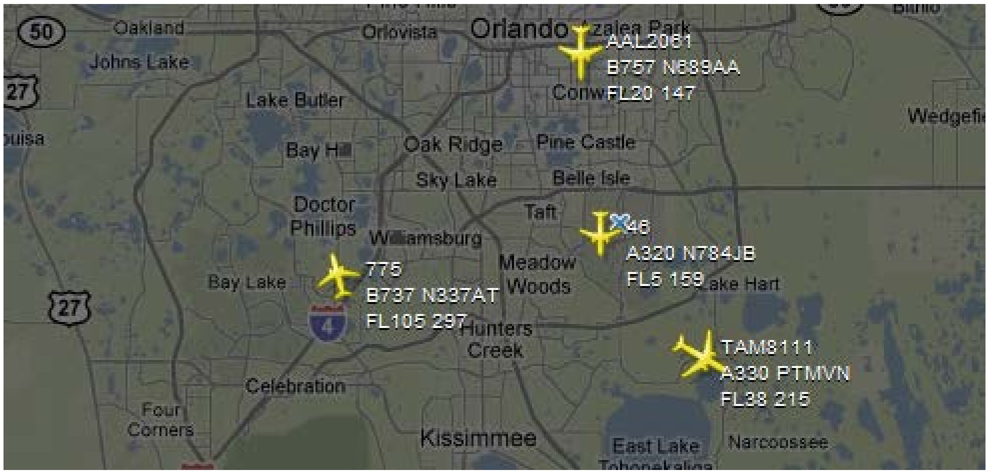

Figure 15. Example of GUI for Flightradar24. From [84].

1. Systems for Non-Cooperative Approach

a. PERCEPTIVU (PVU-Mariner and PVU-Tracker) and MOOG QuickSet GeminEye System

Figure 16 shows the video and tracking set-up consisting of PVU-Mariner, PVU-Tracker and MOOG QuickSet GeminEye System. Most data about the PerceptiVU components are from the user manual [85]; the information summarized in this thesis is meant as a quick reference and is by no means sufficient to replace the manual itself.

The PerceptiVU PVU-Mariner (Figure 20) is a Linux based system for video and radar tracking applications. PVU-Tracker is the embedded application within PVU-Mariner. PVU-Mariner can be used with a QuickSet pan/tilt to accomplish precision video and radar tracking while stabilizing the pan/tilt in two axes against host vessel yaw pitch and roll motion [85]. The QuickSet GeminEye system (Figure 17) is the pan/tilt controllable camera system that was used for our set-up. Table 5 and Table 6 summarize the technical specifications for the PVU-Mariner and MOOG QuickSet GeminEye System (GVS-801) respectively.

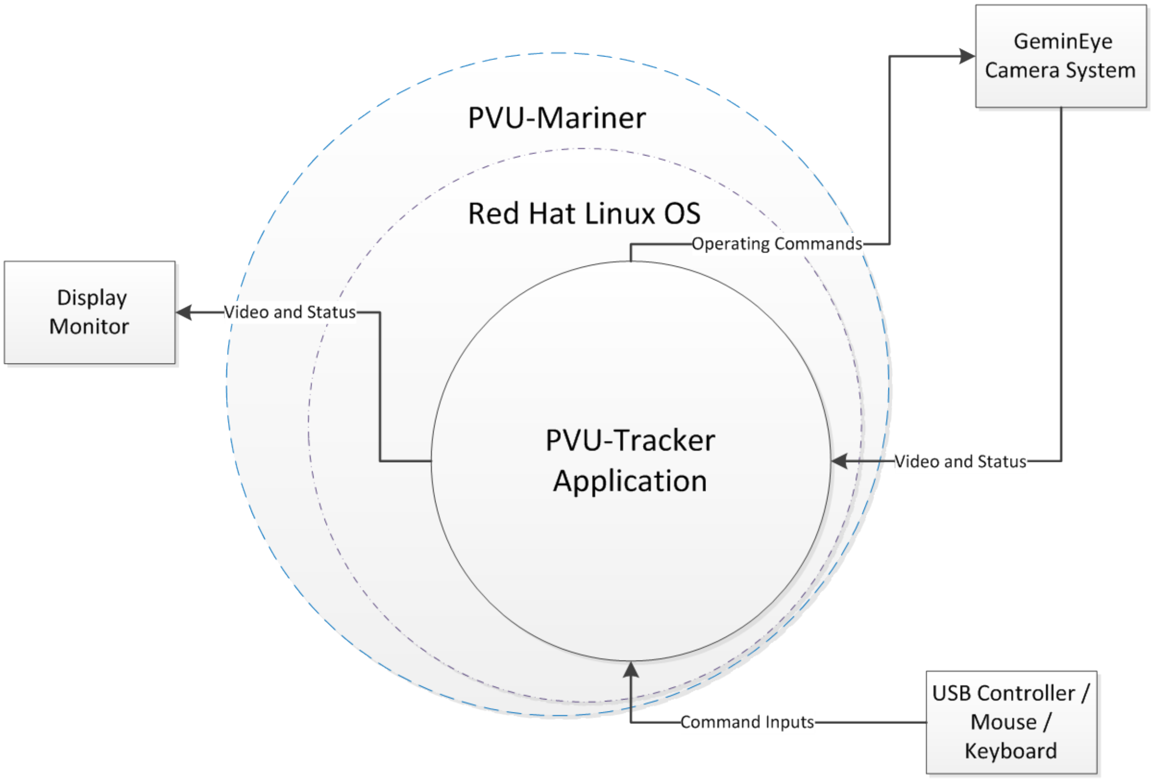

Figure 16. PERCEPTIVU (PVU-Mariner and PVU-Tracker) and MOOG QuickSet GeminEye System Context

Figure 17. MOOG QuickSet GeminEye System

Index	Parameter	Specification
1	Processor	Pentium M – 1.6 GHz
2	Memory	512MB DDR-RAM
3	Communication Interfaces	2x USB V2.0 COM 1, 2, 3 & 4 LAN Ethernet 10/100Base-T RS232 for camera control (Pan/Tilt) TCP/IP for command input and information output
4	Video Input	Up to 4 video channels (NTSC/RS170)
5	Video Output	VGA output
6	Standard Operating Temperature	0 to 50 degree Celsius
7	Weight	< 3 kg
8	Dimension	6.3 x 10.0 x 2.3 inches
9	Power	10 – 16 VDC (3amps at 12V)

Table 5. PVU-Mariner Technical Specification. From [85].

Index	Parameter	Specification
1	Camera Model	Sony 1000
2	Field of View	57.8 – 1.7 degrees
3	Focal	4.7 – 122mm
4	Pan Range	360 degrees (non-HD) / +-180 degrees (HD)
5	Pan Speed	0.25 – 96 degrees per second
6	Tilt Range	+- 90 degrees
7	Tilt Speed	0.25 – 96 degrees per second
8	Weight	Approximately 22lbs (1.0kg) with dual cameras
9	Operating Temperature Range	-40 degree to 50 degree Celsius
10	Position Feedback Resolution	0.01 degrees

Table 6. Consolidated MOOG QuickSet GeminEye System Technical Specification. After [86] and [87].

Figure 18 shows an illustration of the PerceptiVU set-up, and Figure 19 shows a close-up of the QuickSet camera and Figure 20 shows the close-up of the rest of the equipment. Figure 21 shows the connection to the PVU-Mariner equipment. In our set-up, Video Number 2, Com 3 and 4 and Com 2 are not used. The MOOG QuickSet needs an external 12VDC power supply. The red and white wires out of the wire harness are connected to the positive and negative terminals of the power supply, respectively.

Figure 18. PerceptiVU System set-up on building roof-top at NPS

Figure 19. Quickset pan/tilt

Figure 20. PVU-Mariner and PVU-Tracker with display monitor and I/O devices

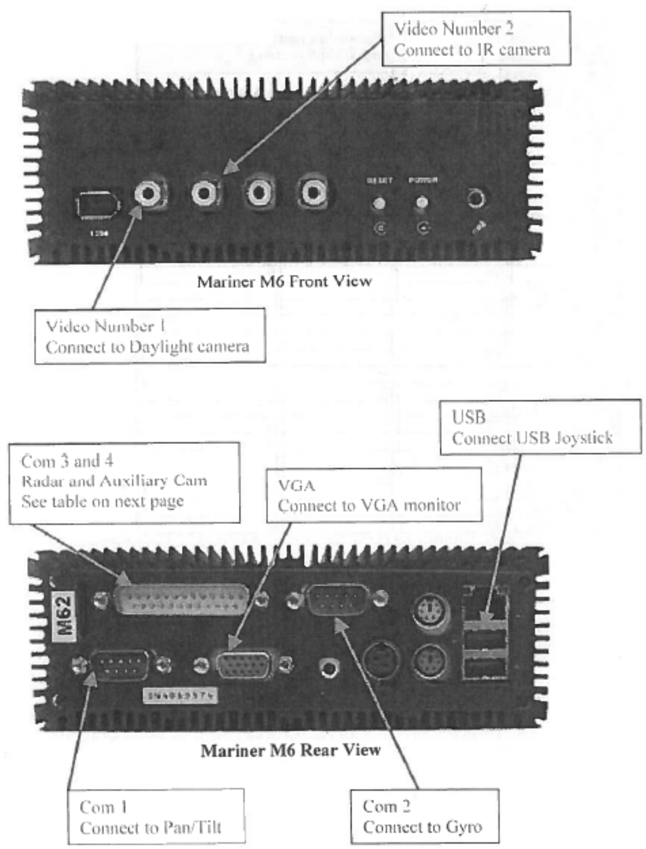

Figure 21. PVU-Mariner Connections. From [85].

The PVU-tracker is capable of nine forms of video tracking, namely Dynamic-Centroid, Hottest Spot, Dynamic Correlation, Boat Tracking, Ground to Air Tracking, Motion, Threshold, Motion on Motion and Scene Track.

(1) Dynamic-Centroid Tracking

The centroid tracking algorithm tracks bounded objects within the track window base on contrast. The algorithm determines the threshold for target selection and also performs morphological processing and blob analysis on each object in the track window. The centroid of each object inside the track window is calculated based on a weighted sum of adjoining object pixels. The algorithm has an auto gate sizing option which allows the system to automatically adjust the size of the gate when tracking is engaged. The user is also able to set the contrast with which the algorithm searches for targets. White Hot dictates a higher intensity target against a lower intensity background; Black Hot dictates a lower intensity target against a higher intensity background; Auto Polarity allows the application to decide if the current target should be tracked based on White Hot or Black Hot by contrasting the average intensity inside the track window with the average intensity on the border of the track window, and Bipolar looks for large extremes from the average intensity within the window. Centroid tracking works well when dealing with a single object with significantly different intensity from the background and the background has little clutter. The algorithm attempts to continue tracking the target of interest, in the case of clutter or other potential targets entering the scene, by knowing the true height, width and trajectory of the target [85].

(2) Hottest Spot Tracking

The hottest spot algorithm tracks the densest block of pixels within the tracker gate. This method is suitable for tracking small objects with high contrast to the background [85].

(3) Dynamic Correlation

This method is best suited for tracking unbounded objects that are difficult to distinguish from the background clutter. Tracking is accomplished by taking a correlation pattern of the object inside the crosshairs when the user engages the tracker and scanning every subsequent frame for the “best match” to the correlation pattern. The algorithm has the ability to realize when the system is tracking with decreasing certainty and re-learn the changed pattern in real-time, allowing tracking of objects even as they become partially occluded or change in scale, shape or orientation. The algorithm forces the system into "Auto-Reacquire" if a track is lost. In this mode, the system successively enlarges the region of search and "coast" for the camera in order to reacquire the object. The algorithm does not require the presence of "Hot Spot" and works even with a relatively high amount of clutter. However, the method requires the tracker to be engaged only when the desired pattern is directly in the crosshairs and can be difficult for fast moving targets. This method is best used when tracking a large target that has plenty of pixel texture [85].

(4) Boat Tracking

The boat tracking algorithm is designed to track fast moving boats in standard EO daylight imagery and does not necessarily require a thermal IR imager. The algorithm finds man-made objects and attempts to disregard waves and the horizon. [85]

(5) Ground to Air Tracking

This algorithm is designed for tracking airplanes in the sky from a ground based camera. The algorithm is designed for standard EO daylight imagery and does not necessarily require a thermal IR imager. The algorithm searches the entire image and is not limited to a gate [85].

(6) Motion Tracking

This algorithm searches the entire image for motion (requires the camera position to be fixed) and can find up to 50 objects per frame. The algorithm draws green boxes around objects found, and the object data is available via TCP interface. It is recommended to refer directly to the original user manual document for a description of the TCP interface [85].

(7) Threshold Tracking

The algorithm searches the entire image for objects either below or above the predefined pixel threshold level. The algorithm is capable of finding up to 50 objects per frame and draws green boxes around all objects found by the algorithm. The threshold level is set through the TCP interface and object data are also available through the TCP interface [85].

(8) Motion on Motion Tracking

The motion tracking algorithm takes into account motion due to camera pan/tilt motion. The algorithm determines the effect of the camera movement and accounts for the difference before performing pixel subtraction for motion detection [85].

(9) Scene Tracking

This algorithm is designed to track a scene. Previous images were compared to the current image to determine the amount shifted. The algorithm then commands the corresponding pan/tilt to compensate for the shift and attempt to maintain the track on the scene. The purpose of the algorithm is to stabilize the imagery when the platform on which the camera is placed has pitch and roll motion [85].

b. SkyIMD SkyFusion Pak 2000

Figure 22 shows the components of the SkyFusion Pak 2000 and the connection between the components. The major components are the Camera Pod and Gimbal, Advanced Imaging System, Flight Laptop and USB controller. The AirCard was not used in our set-up. The sensor assembly within the camera pod and gimbal is a TASE 200 (Figure 23) by Cloud Cap Technology. Table 7 summarizes the technical specifications for the TASE 200 system.

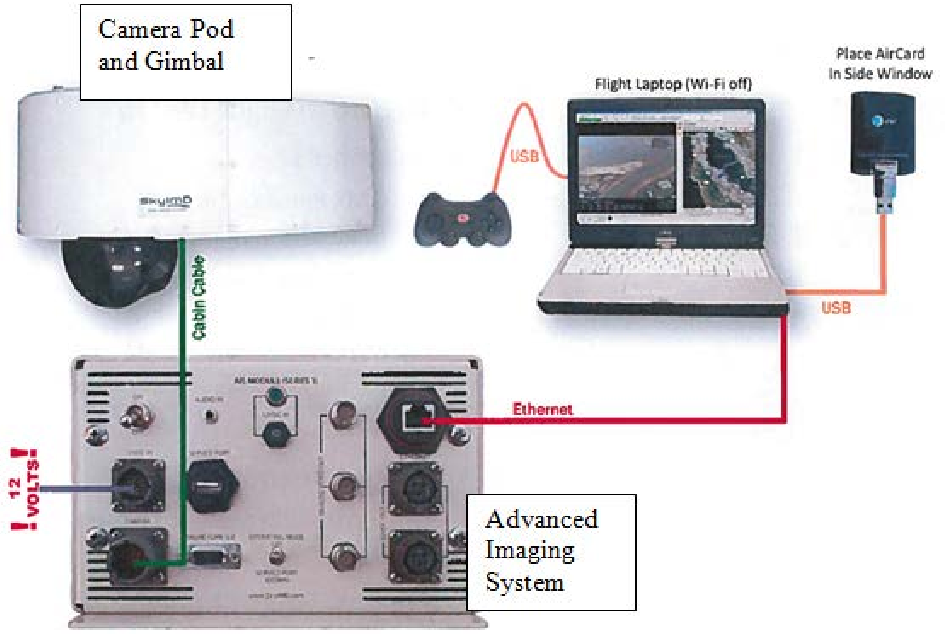

Figure 22. SkyFusion Pak 2000. From [88].

Figure 23. TASE 200 Stabilized Gimbal and EO/IR Cameras. From [89].

Index	Parameter	Specification
1	Camera Model	EO: Sony FCB-EX 1020 LWIR: FLIR TAU 640
2	Field of View	EO: 55.7 – 1.94 degrees LWIR: 10.5 degrees
3	Focal	EO: 36 x Optical LWIR: 59mm
	Resolution	EO: 380k pixels LWIR: 640 x 480 pixels
4	Pan	Continuous
6	Tilt Range	-203 degree to 23 degree
7	Slew Rate	200 degrees per second
8	Weight	1.06 kg (2.34 lbs.)
	Dimension	Gimbal: 122 x 115 x 192mm (4.7 x 4.5 x 7.5 inches) (4.7 x 4.5 x 7.5 inches) Turret (diameter): 115mm (4.5 inches)
9	Operating Temperature Range	-20 degree to 70 degree Celsius (not valid for camera)
10	Position Feedback Resolution	873 X 10^{-6} radians

Table 7. Consolidated TASE 200 Technical Specification. After [89] and [90].

C. EXPERIMENT DESCRIPTION

1. Use of Stratus 2 Set-up

In order to derive the requirements for situational awareness and avoidance of collision between UAVs or between UAV and manned aircraft, there is a need to have a reference for comparison. The operating requirement for manned aircraft in the context of avoiding collision is matured. For the manned aircraft, the most basic way to avoid collision is to see and avoid other aircrafts. An experiment was conducted to provide a better appreciation of the interactions in play in the reference method (see and avoid) and to understand the existing systems in place (ATC system and regulations) to mitigate the risk of mid-air collision. Another objective of the experiment was also to understand the benefits ADS-B information to the pilot in terms of situational awareness.

The experiment with Stratus 2 involves using the Stratus 2 set-up to observe surrounding traffic while flying as a passenger beside the pilot on a general aviation aircraft. The attempt to visually locate aircraft that are reflected to be near the system was found to be considerably challenging. It would have been very beneficial if we had been able to install the SkyIMD set-up on the plane, but the equipment was not pre-certified for the particular model of Cessna that we flew on, and hence we had to fly without the SkyIMD visual tracking equipment.

2. Use of PerceptiVU and SkyIMD Set-ups

In the context of piloting a UAV, the pilot is not onboard the aircraft. Situational awareness cannot be achieved through directly observing the environment using the pilot's eyes and must be provides through other indirect means.

ADS-B and DRR are examples of means to obtain information about the UAV surrounding. The information can then be present to UAV pilot to provide situational awareness. ADS-B in particular is a good system which allows a pilot to be aware of traffic within his aircraft vicinity at distances beyond visual line of sight range. An obvious requirement before ADS-B can perform its functions is the need to place all participating aircraft with at least ADS-B OUT.

The experiment with the PerceptiVU and SkyIMD set-ups involves assembling both systems on the rooftop of Spanagel Hall in NPS and attempting to track general aviation aircraft taking off from or landing at the Monterey Peninsula Airport and other aircraft passing by NPS (Figure 24). The task involves using USB controllers to steer respective cameras onto the aircraft of interest and activating the tracking functions of the respective set-ups. The task proved to be challenging, and we had our fair share of success and failures. We quickly realized the task would have beeb much easier if we had indications of surrounding air traffic before potential targets to be tracked came within visual range. In addition, it would have been much more useful if we had the corresponding information regarding the model of the aircraft, the flying altitude, airspeed, etc., of the aircraft we were tracking. The Flightradar24 application was used to provide the information we required. Figure 25 shows the tracking of an Airbus A320, flying at 20,000 feet and at 370 knots, using the Dynamic-Centroid Tracking algorithm of the PerceptiVU equipment. Figure 26 shows the tracking of the same aircraft using a SkyIMD set-up. Figure 27 and Figure 28 show other examples of tracking general aviation aircraft, using the PerceptiVU and SkyIMD set-ups, respectively. Figure 29 shows tracking of aircraft using images from the IR camera.

Figure 24. Aircraft Tracking with PerceptiVU and SkyFusion Pak set-ups

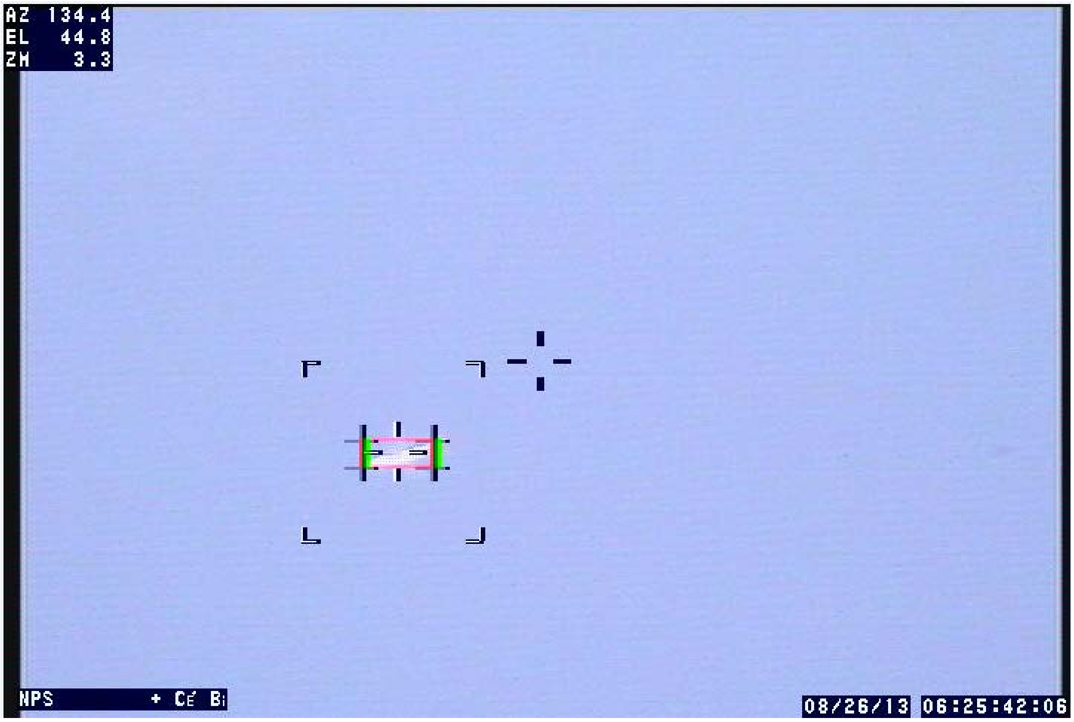

Figure 25. Tracking of A320 aircraft with PerceptiVU set-up

Figure 26. Tracking of A320 aircraft with SkyFusion Pak set-up

Figure 27. Tracking of general aviation aircraft using PerceptiVU set-up

Figure 28. Tracking of general aviation aircraft using SkyIMD set-up

Figure 29. IR tracking using SkyIMD set-up

D. DISCUSSION ON OPERATIONAL REQUIREMENTS

The major takeaways from the experiments are the difficulty involved in visually spotting other aircraft within the vicinity from the cockpit of an aircraft and the difficultly of tracking an aircraft using visual sensing equipment such as the PerceptiVU and SkyIMD set-ups.

Regarding the difficulty involved in visually spotting other aircraft, two possibilities were considered. First, air traffic control elements ensured sufficient separation between aircraft, causing other aircraft to be beyond visual detection range. Second, significant challenges exist in trying to visually spot another aircraft flying within the vicinity. Both assumptions are probably concurrently valid for the context of this experiment. In the experiment, the aircraft that was flown and the class of airspace the aircraft was flown in limits the aircrafts that could be spotted (aircraft that are actually flying in the vicinity) to other general aviation aircraft. A Cessna general aviation aircraft, depending on model, can be around 27 feet in length and 36 feet in wingspan and having a maximum cruise speed of 124 knots[13] [91]. The size of the aircraft and flying speed are similar to a larger UAV such as a Predator. The Predator UAV has a length of 26.7 feet and wingspan of 48.7 feet and a maximum loitering speed of 118 knots [43]. There is good reason to believe that the experience was a good representation of the context of trying to visually spot a UAV flying in the vicinity.

Regarding the difficulty involved in tracking an aircraft using visual sensing equipment, two challenges were significant. The first challenge was associated with trying to manually steer the camera to obtain a view of the aircraft of interest and at the same time controlling the zoom to obtain a sufficiently large image of the aircraft for the tracking algorithm. The difficulty was caused in part by a disassociation between the location of the camera view and the location of the aircraft of interest from the perspective of the person performing the control. The other factor was the sensitivity of change in the location of the camera view when the camera set-up was commanded to a significant amount of zoom; the impact of this factor is reduced when the distance between the sensor and the aircraft of interest is short (requiring less zoom). However,

[13] Specification based on Cessna Skyhawk aircraft.

the savings are usually offset by the need to complete the process of steering the camera onto the aircraft and executing the tracking function. Note that angular movement, and hence the rate of the angular change, required to follow an aircraft travelling at the same speed at a near distance is larger than if the aircraft is at a great distance (Figure 30.). Although a number of attempts to track commercial aircraft that flew directly over the camera set-ups after taking off from the nearby Monterey Peninsula Airport were attempted, the task was never successfully completed until the aircraft had travelled significantly far and the rate of motion of the aircraft from the perspective of the author's location was relatively slow. It would have been beneficial to have the aircraft altitude and airspeed information of those failed attempts for study of the rate of pan and tilt movement requirement to be successful in the tracking attempts; it was unfortunate that such opportunities no longer presented themselves after the Flightradar24 application was used. The other challenge was executing the track function on the aircraft. Factors such as the difficulty of moving the tracker gate onto the aircraft (required for certain tracking algorithms) and the inability of the algorithm to distinguish the object of interest or maintain track contributed to making the task a challenge.

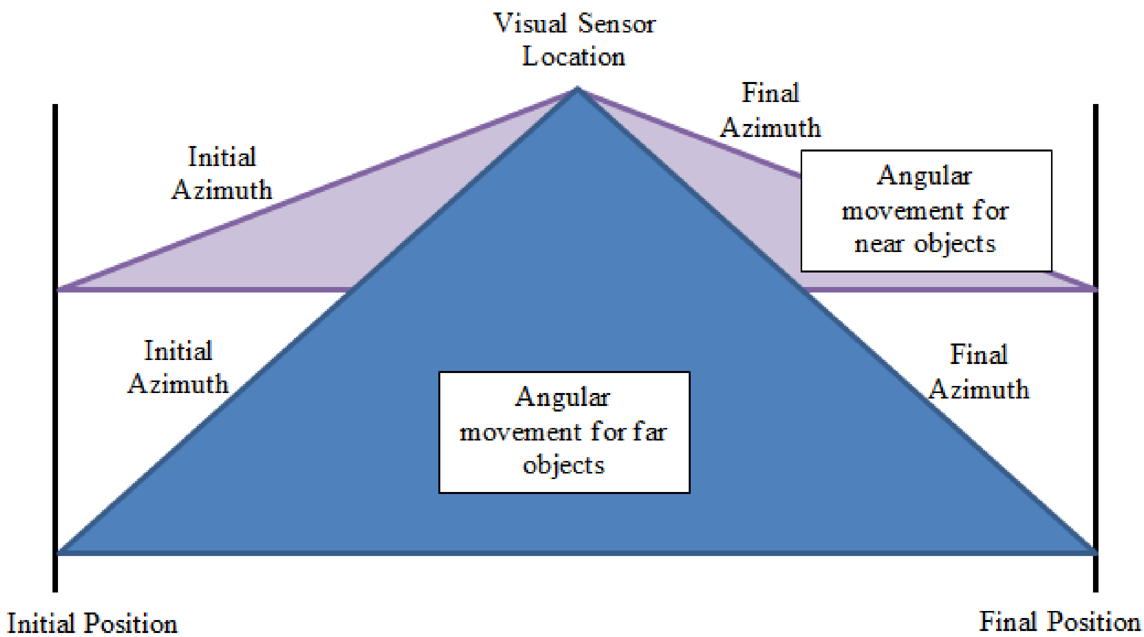

Figure 30. Illustration of change in angular movement required with respect to change is distance between sensor location and object of interest

In the context of collision avoidance for a UAV pilot using visual sensor systems such as the cameras used for the PerceptiVU and SkyIMD set-ups, the author had a number of advantages over the UAV pilot situated remotely in his control station. Without going into issues regarding the possibility of communication loss and issues such as latency of the visual information due to communication delay or loss of quality of video due to compression (to keep the discussion general and relevant even in the context of implementing onboard collision avoidance capability using visual detection as the means for detection), it was possible to scan the surroundings with a wide field of view (approximate span of human vision is 120 degrees and greater), it was possible to scan the surroundings without losing a sense of the general direction of the view relative to the aircraft, and there was significant freedom to adjust the position of the author's head to overcome potential obstruction of view.

Summing up the experience, the following lessons were learned:

- A visual sensor set-up alone is probably insufficient to give a UAV pilot a good interpretation of air traffic around the aircraft.
- A system design requiring the pilot to perform steering and tracking controls of visual sensors for the purpose of potential collision threats is probably not feasible.
- The location of visual sensor on the aircraft is an important consideration.
- Substantial design consideration into HMI is needed, especially in the aspect of presentation of information and the mechanism for operation and control.

A visual sensor alone is insufficient for a number of reasons. As mentioned previously, during the description of the experience in the cockpit, the author had a number of advantages over a UAV pilot sitting remotely in a control station. The wide field of view of human vision allowed efficient visual scan of the surroundings. It was also found to be much easier to relate the view with the surroundings and make interpretations (including estimated interpretation of relative speed of object of interest, distance of object, path of motion, etc.) compared to being limited to vision through a visual sensor. It was also much easier to reacquire the object of interest after losing sight of it when the author was viewing the surroundings directly through his eyes. For a UAV pilot assisted by only visual sensor, a rough estimation of distance probably needs to be done by using judgment to relate the size of the aircraft on the video display to the numeric value of camera field of view (after zoom), and motion information needs to be inferred from a numeric value indicating angular velocity of camera movement. In the context of understanding the surroundings through the vision of a visual sensor, the limited FOV of the sensors (57.8 degrees and 55.7 degrees for the PerceptiVU and SkyIMD set-ups respectively), the difficultly of maneuvering the sensor onto the object of interest and executing a successful track, the disassociation between the task being performed and the information feedback will collectively put a UAV pilot in a highly unfavorable position. In the experiments involving tracking aircraft with the respective set-ups, there was luxury of having both the camera and the aircraft of interest in the author's visual sight and it was possible to align the pointing direction of the camera to the aircraft of interest through estimation. The camera view was first placed on a point of reference (e.g., the top of a tree) and through judgment of the relative position of the aircraft of interest with the chosen point of reference, an interpretation of the control needed to adjust the camera onto the aircraft was then made. During the process of trying to acquire a view of the aircraft, the physical pointing direction of the camera was constantly compared with the direction of the aircraft of interest through visual inspection and estimation. This is a luxury that a UAV pilot situated remotely certainly will not have; and even with the mentioned advantage, it was a challenge to orient and reacquire a view of the aircraft of interest after losing sight of it on the camera view. Finally, it was not an easy task just trying to visually spot an aircraft in the vicinity while seated in the cockpit of a flying aircraft; the Stratus 2 set-up played a large part in providing the initial awareness. The challenge will definitely be greater for someone seated a distance away, looking at the camera view on a screen. It is recommended that visual detection needs to be supplemented by methods that provide "broad view" awareness (e.g., ADS-B), and the visual sensor can be used to investigate potential danger after being "cued" by the broad view implementation.

The difficulty of performing the tasks of steering the camera onto the target and subsequently executing a successful track was already described. The author had an abundance of advantages over what a UAV pilot using a similar set-up would have, and he was performing the respective tasks focusing at one task a time without having to worry about flying an aircraft. Nevertheless, the tasks had proven themselves challenging. The author’s limited experience as a sensor payload operator was considered, but better ways to perform the tasks are probably required was the conclusion that was drawn. The author would imagine, in the context that ADS-B information is available, having the system automatically handling the azimuth and elevation control after the user has indicated the desired aircraft to track would have been much easier.

There was significant freedom to move the author’s head to overcome potential obstruction of view while being seated in the cockpit of the aircraft. The same luxury is unlikely applicable to a context where a visual sensor is used. The location to place the sensor and the rest of the payload to achieve unobstructed view of the desired area could be a significant design consideration.

Finally, having emphasized the difficulty of performing the various tasks and explaining the disassociation of information feedback with the task being performed, improvement to the ways of performing the tasks and how information is presented is required. A way which could reduce the difficulty of the tasks was described. Intuitive visual presentation of data to aid the task of interpreting available information could definitely have a significant impact.

VI. CONCLUSION AND RECOMMENDATIONS

A. SUMMARY

This thesis provides a broad-based literature review into the topic of interest—Field applications for Multi-UAVs cooperation missions—from a high level of abstraction. The work summarized in this thesis is far from all-encompassing but nevertheless consolidates information from across various domains, supporting system assessment and design analysis in the context of multi-UAV cooperation/collaboration.

There are a few remaining technical and political obstacles that need to be overcome for multiple UAV operations. The key technological elements include collision avoidance, GPS denied navigation, autonomy, communication network, interoperability and power. The political issues span the gamut of the questions on the legality of use regulations not keeping pace with UAS developments to pressure from human rights organizations and political leaders.

The ADS-B, part of Federal Aviation Administration (FAA) larger airspace modernization efforts and an element with significant amount of mention in discussion regarding integration of UAS into National Airspace System (NAS), seems to offer much promise as a platform to answer many questions regarding the requirements to safely operate UAS with other manned aviation elements. Successful integration of UAVs into commercial airspace will likely provide a design reference and serve as a platform that provides more opportunities to obtain relevant data for study. In addition, the success could help boost confidence and shape general acceptance of operating UAVs with other aircraft (including other UAVs) in no-segregated airspace [4]. The tasks for full implementation of ADS-B and other measures are planned to be completed over the years to follow. Conditions are probably still not right for an ambitious attempt at elaborate designs to handle multiple high-risk requirements, a potential lesson learned from the Future Combat System (FCS) development. FCS was the United States Army's major research, development and acquisition program, consisting of 14 manned and unmanned systems tied together by an extensive communications and information network [5]. FCS, a high-risk venture that was eventually halted in 2009 [5], was criticized in a GAO report for reasons such as critical technology demonstrated being well short of a program halfway through its development schedule and budget [6]. However, there are numerous research papers in various technical domains with relevance to multi-UAVs applications that have been published [7]– [13], suggesting there may be sufficient maturity across domains to begin assessment studies or conduct of experiments which take into consideration multi-dimensional constraints and to begin a progressive evolution towards the desired vision for multi-UAV applications.

Several writers who follow military news and write about military applications [3] and [14] discuss interest (for example, the U.S. Navy interest in Unmanned Carrier-launched airborne surveillance and strike) and capabilities for UAS, while there is an absence of published CONOPs from any military service in the public domain. A CONOPS is a description of how users will employ a product or service. This description is normally both qualitative and quantitative. CONOPS (or ConOps) are always included in any government request for information (according to a private communication with Professor Gary Langford, NPS). Validation of the information that comprises a CONOPS is merely to point out that the information is appropriate and fit for its stated use. The CONOPS is used to guide validation of the user's needs and to help guide the validation planning, testing, and eventually the validation of the system. The other key obstacles to full disclosure on military interest in UAS are the human-related factors, regulations and legal restrictions. The "UAV revolution," like any form of change, must overcome the tendency of humans to resist change. Although reports from military services [1] and other government agencies [15] and [16] have shown the operational value of UAVs, full scale adoption remains thwarted by the technical and political obstacles mentioned. Legislation, regulations and standards need to be considered and revised along with the concerns of the regulatory and legal authorities.

Some lessons were learned from the conduct of an experiment using ADS-B and visual tracking equipment to understand the operating challenges and requirements of using these equipment to provide situation awareness for the UAV pilot. First, a visual sensor set-up alone is probably insufficient. The combined effect of limited field of view, difficulty of maneuvering the sensor onto the aircraft and executing a successful track, the disassociation between the task being performed and the feedback received will likely put the UAV pilot in a highly unfavorable position. In addition, having another mechanism (such as ADS-B information) to provide “a broad view” to supplement the “narrow view” from the visual sensor is probably beneficial. Second, the mechanism requiring the pilot to perform steering and execute tracking is probably not feasible. The task was challenging even when the author had both the aircraft and the equipment within his sight, and he was performing the task without having to worry about flying an aircraft. Third, consideration for the position of the visual sensor is important. The sensor needs to be placed at a location where unobstructed view of any location within the intended area to monitor is guaranteed. Lastly, design considerations to improve the presentation of information and the mechanism to operate and control the equipment are required. Even with his advantages, the author found the correlation between the tasks being performed and feedback to be low. The lack of significant variation in the background (the sky) caused the author to lose track of the orientation easily. All attempts to track commercial aircraft taking off from Monterey Peninsula Airport and flying directly over NPS failed. The time available to perform correlation between the task of steering and receiving feedback, while at the same time controlling the zoom and executing the track,was simply insufficient.

B. CONCLUSION

With regard to the primary research question on state of research related to technology readiness and efficient deployment, the thesis consolidated a large amount of information to facilitate the conduct of systems engineering activities, identified a number of areas perceived as potentially important to be considered when performing systems engineering related activities for multi-UAV area of applications, provided an interpretation of the status of the respective areas and finally conducted an experiment to study the operational challenges of using ADS-B and EO/IR cameras for situational awareness.

The operational areas of interest the areas of applications that had generated a significant amount of research interest and discussion were narrowed to Urban Operations, Communications Support, Collaborative Sensing, Swarm (Wide area search, EW, Offensive and Defensive) and Loyal Wingman applications. The factors driving the interest for these applications (to address user needs) were the need for timely and updated intelligence regarding a dynamic urban environment, need for affordable connectivity with sufficient bandwidth and a desire to capitalize on opportunities made feasible with small UAS. In addition, the desire to do more with unmanned systems and the a need to reduce manpower and logistics requirement associated with operating UASs also play a part in attracting operational and research interest. The primary technical areas, such as collision avoidance, Global Positioning System (GPS) denied navigation, autonomy, communication network, interoperability and power, were discussed in depth, including some of the algorithms being researched for the respective applications.

There are a few remaining technical and political challenges. The key technological elements are still being matured. The political issues span the gamut of questions on the legality of use and regulations not keeping pace with UAS developments to pressure from human rights organizations and political leaders.

The experiment conducted studied the operating challenges and operating requirements of using ADS-B and visual tracking equipment to provide situational awareness.

C. RECOMMENDATIONS

There are a number of models used in research from NPS students. It is recommended to look into using the integration of the models to introduce more constraints in the study of the respective areas of interest. For example, collision-free path generation needs to be incorporated into the mechanism for sensing and detection before the function is complete and could find applications. With regards to future improvement for the experiment, the SkyFusion Pak system is already intended to be installed and used on board a general aviation aircraft. For future research, it is recommended to ensure, when examining organic UAV collision avoidance, ADS-B data (such as altitude and airspeed) of the aircraft being tracked and the corresponding airspeed information of the investigator’s own aircraft are recorded and related to the video recordings or image capture from the tracking activities.

It is also recommended to expand the scope of information consolidation to address other aspects of Systems Engineering, such as Project Management. The conduct of Systems Engineering studies and Gap Analysis studies for different areas of multi-UAVs system applications or assessment of detailed system design using the information consolidated with this thesis will be a desired outcome.

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