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**STREAMLINING THE CHANGE-OVER PROTOCOL FOR THE RPA MISSION  
INTELLIGENCE COORDINATOR BY WAY OF SITUATION AWARENESS  
ORIENTED DESIGN AND DISCRETE EVENT SIMULATION**

THESIS

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AFIT/GSE/ENV/12-M06

**DEPARTMENT OF THE AIR FORCE  
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***AIR FORCE INSTITUTE OF TECHNOLOGY***

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ORIENTED DESIGN AND DISCRETE EVENT SIMULATION

THESIS

Presented to the Faculty

Department of Systems and Engineering Management

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the  
Degree of Master of Science in Systems Engineering

John P. Machuca, BS

Captain, USAF

March 2012

DISTRIBUTION STATEMENT A. APPROVED FOR PUBLIC RELEASE;  
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## **Abstract**

Incredible loiter times coupled with the ability to make extremely detailed collections at significant stand-off distances with a relatively expendable platform has made demand for, and diversity of RPA operations grow at voracious rates. Conversely, financial resources are becoming increasingly constrained. As such innovators are looking to maximize the effectiveness of existing personnel and assets by considering concepts such as simultaneous Multiple Aircraft Control (MAC) by a single aircrew.

Research has identified procedural inefficiencies in current operations as well as substantial impediments to MAC implementation including dynamic task saturation and communication challenges. An identified inefficiency afflicting both current operations and the feasibility of MAC is the time required to transfer operational situation awareness at shift change – dubbed “change-over”. The present research employed synergistic application of Cognitive Task Analyses, Situation Awareness Oriented Design and simulation to inform the development of a highly efficient user-centered process for the Mission Intelligence Coordinator – the RPA aircrew’s situation awareness linchpin. Discrete-event simulations were performed on existing and proposed protocols. These analyses indicate that the proposed protocol could require as little as one-third the time required by the current method. It is proposed that such an improvement could significantly increase current RPA mission-readiness as well as diminish a known obstacle to MAC implementation.

*To my beautiful wife and incredible family. Thank you for your patience, support and above all, your love.*

## **Acknowledgments**

I would like to express sincere appreciation to Lt Col Anthony Tvaryanas and the 711th Human Performance Wing as well as the professionals of Creech AFB. Without your personal and organizational support this research would have been neither possible, nor relevant. And to my advisors and thesis teammates – I say thank you for the immense assistance you've provided me during my time here, but more importantly for making the experience a truly productive, enjoyable and memorable one.

John P. Machuca



## Table of Contents

|  | Page |
|--|------|
| Abstract.....  | iv   |
| Acknowledgments.....   | vi   |
| Table of Contents.....   | vii  |
| List of Figures.....   | ix   |
| I. Introduction .....  | 1    |
| Background .....   | 1    |
| Problem Statement .....  | 2    |
| Research Objectives .....  | 3    |
| Research Focus.....  | 4    |
| Investigative Question.....  | 5    |
| Methodology .....  | 5    |
| Assumptions/Limitations .....  | 6    |
| Preview.....   | 7    |
| II. Scholarly Article .....  | 9    |
| Abstract .....   | 9    |
| Introduction.....  | 10   |
| <i>Problem Statement</i> .....   | 13   |
| <i>Research Objectives</i> .....   | 14   |
| <i>Investigative Question</i> .....  | 15   |
| Background .....   | 15   |
| <i>Situation Awareness</i> .....   | 15   |
| <i>Situation Awareness Oriented Design</i> .....                                   | 18   |
| <i>Cognitive Task Analysis</i> .....   | 21   |
| <i>Change-over</i> .....   | 23   |
| Methodology .....  | 26   |
| <i>Overview</i> .....  | 26   |
| <i>Step 1. Cognitive Task Analysis of current change-over process</i> .....        | 27   |
| <i>Step 2. Creation of current process architecture model</i> .....                | 28   |
| <i>Step 3. Application of Situation Awareness Oriented Design principles</i> ..... | 30   |
| <i>Step 4. Creation of the new process model</i> .....                             | 33   |
| <i>Step 5. Statistical analysis of current and proposed model output</i> .....     | 36   |
| Assumptions and Limitations.....   | 37   |
| Results.....   | 38   |
| Conclusion .....   | 39   |
| Future Research.....   | 40   |

|  |    |
|--|----|
| References .....   | 42 |
| Appendix A. Example knowledge representation of current process chronological CTA data ..... | 44 |
| Appendix B. Example knowledge representation of goal-based CTA data .....                    | 45 |
| Appendix C. Scholarly Article - Allocation of Communications to Reduce Mental Workload.....  | 46 |
| Abstract .....   | 46 |
| Introduction .....   | 47 |
| Background .....   | 48 |
| Method .....   | 49 |
| <i>Model</i> .....   | 49 |
| <i>Experimental Design</i> .....   | 52 |
| Results .....  | 53 |
| Conclusions .....  | 54 |
| References (Appedix C).....  | 55 |

## List of Figures

|  | Page |
|--|------|
| Figure 1. Aircrew Interaction Diagram.....   | 13   |
| Figure 2. Situation Awareness Oriented Design Process.....                             | 18   |
| Figure 3. Current Change-over Process Arena Model.....                                 | 29   |
| Figure 4. Proposed Change-over Process Arena Model .....                               | 35   |
| Figure 5. CO Change-over Process Duration PDFs.....                                    | 39   |
| Figure 6: Modified communication model of pilot workload .....                         | 51   |
| Figure 7: Percent Time Over Threshold as the percentage of reallocated voice events .. | 54   |

# STREAMLINING THE CHANGE-OVER PROTOCOL FOR THE RPA MISSION INTELLIGENCE COORDINATOR BY WAY OF SITUATION AWARENESS ORIENTED DESIGN AND DISCRETE EVENT SIMULATION

## I. Introduction

### Background

Military, government and commercial industries across the globe have only recently begun to realize the potential benefits of medium and high-altitude Remotely Piloted Aircraft (RPA) technologies. Consequently the demand for RPA operations, especially within the US Air Force, has grown at insatiable rates. In a 2010 federal hearing on unmanned systems and the future of war, US House of Representatives Subcommittee on National Security and Foreign Affairs Chairman John F. Tierney quantified current trends, “As the United States is engaged in two wars abroad, unmanned systems, particularly unmanned aerial vehicles, have become a centerpiece of that war effort. In recent years, the Department of Defense’s inventory has rapidly grown in size, from 167 in 2002 to over seven thousand today. Last year, for the first time, the US Air Force trained more unmanned pilots than traditional fighter pilots.” (Tierney, comments made 23 March 2010). Furthermore, the US Air Force Unmanned Aerial System Flight Plan 2009-2047 (pp 15) stated, “UAS have experienced explosive growth in recent history, providing one of the most “in demand” capabilities the USAF presents to the Joint Force. The attributes of persistence, efficiency, flexibility of mission, information collection and attack capability have repeatedly proven to be force multipliers across the spectrum of global Joint military operations.”

Clearly, Department of Defense (DoD) leaders have come to recognize the power

and economy of RPA technologies, and see them as strategic solutions to the omnipresent requirement to find new ways to do far more with far less. Battlefield commanders relish the thought of persistent and detailed real-time knowledge of activities on the battlefield while strategically deploying limited ground resources. Today's front-line warrior yearns for the substantial tactical advantages of timely and effective close air support (CAS) from their RPA escorts. At all levels, RPA technologies have become imperative to modern warfare, and there is little doubt that the robotic extension of the human warfighter has permanently changed the way battles are planned, waged and won.

### **Problem Statement**

The immense power of these technologies has led to an unrelenting appetite for RPAs to do even more – more sorties, more flight hours, more data collection, more coverage. The reality, however, is to do more, substantial resources must be dedicated and expended. In today's fiscal environment, this simply is not feasible and innovators have been charged to find RPA force-multiplying efficiencies to assist in bridging current and foreseeable resource/demand gaps with ever decreasing resources.

To that end, research is ongoing to maximize the effective utilization of existing RPA assets, up to and including the concept of a single aircrew controlling multiple aircraft simultaneously, referred to as Multiple Aircraft Control (MAC). A common challenge facing both MAC and current operations is the amount of time existing protocols require to efficiently transfer situation awareness (SA) at shift change – dubbed “change-over”. Analyses have concluded that change-over activities can consume up to 10% of a pilot's mission time in single-aircraft control (Schneider & McGrogan, 2011).

In a MAC scenario, if a pilot accepts control of three or four aircraft, the subsequent transfer time and effort can rapidly balloon to consume an unreasonable percentage of the pilot's effective mission time. Similar challenges and results are anticipated for the rest of the aircrew to include the sensor operator and mission intelligence coordinator (MICs). Such a reduction in effectiveness runs counter to the intended objectives of MAC implementation.

### **Research Objectives**

The objective of the present research is to use disciplined and pedigreed methods to reduce the duration of time required to accomplish the transfer of operational SA from a losing crew to a gaining crew at change-over in single aircraft control. Doing so could increase the mission capability of current RPA forces, as well as validate the use of such methods to inform the subsequent design of a MAC change-over protocol.

Furthermore, RPA industry-wide, literature does not yet exist on change-over processes and specific design recommendations despite medium and high-altitude RPAs being used in numerous civil and military applications. Similarly, a literary gap exists with respect to the operational information requirements of the RPA MIC. While such analyses have been conducted on pilots, particularly in manned aircraft, no such research has been published with respect to the role of the MIC. This research serves to address these gaps.

## **Research Focus**

The primary purpose of change-over is for the on-coming crew to achieve sufficient understanding of the current state of all operationally pertinent information prior to assuming full control of the aircraft. While the duration required to accomplish change-over is an issue affecting the entire aircrew, the decision was made to focus the present analysis on the role of the MIC. The MIC's primary role is to act as the team's communication focal point - integrating, filtering and passing information between the aircrew and the numerous external parties. Both the pilot and sensor operator have responsibilities that often fully tax their individual cognitive resources - particularly during dynamic events such as targeting, weapons employment or an in-flight emergency. It is during these times, ironically, that the speed, volume and relevance of communication are the most severe. Third parties including the squadron chain of command, intelligence sources, friendly ground and air forces, and the customer must exchange extremely time-sensitive information continuously and reliably with the RPA crew. Any missed communication or delay of message receipt could very easily mean the difference between mission success and catastrophic failure.

In these situations, communication directly translates to situation awareness exchange – both amongst the crew and the external parties. It is for this reason that the MIC, as the aircrew's primary communication, and therefore SA processor, was chosen as the focus of the analysis.

## **Investigative Question**

The present research attempts a redesign of the RPA MIC change-over protocol from the current technology-centered process to a user-centered process. The redesign is predicated upon Situation Awareness Oriented Design (SAOD) protocols and principles. The basic investigative question is, how can the current change-over process be redesigned to facilitate more expedient transfer of SA? It is hypothesized that converting the design to a user-centered design could lead to a significant reduction in process duration, thereby increasing RPA operational availability.

## **Methodology**

This analysis consisted of five primary steps. First, a cognitive task analysis (CTA) of the current MIC change-over process was completed to identify each of the individual root knowledge elements, or essential elements of information (EEIs), which must be exchanged at change-over for a receiving MIC to achieve sufficiently operational SA. In other words, the CTA effort identified each of the specific data points that a gaining MIC must know to be able to safely and successfully assume control of a mission. The second step was the creation and evaluation of the current process architecture model within Rockwell Automation's discrete-event simulation software Arena. Within this step, each of the process's individual tasks were enumerated and represented. Duration estimates and distributions for each were obtained from subject matter experts and built into the model. Arena was then used to conduct Monte-Carlo simulations to gain insight into the duration and variability of the process. Next, the SAOD principles and heuristics were applied to the various types of root data identified



by the CTA, enabling highly efficient and disciplined design of an improved change-over construct, carefully built around the goal of effective and efficient SA achievement. The fourth step was to translate the newly designed change-over system definition into Arena for evaluation. Finally, statistical analysis on the output from the current and proposed Arena model runs was accomplished with resultant conclusions and operational implications drawn.

### **Assumptions/Limitations**

For the current change-over process model, subject matter experts provided input and subsequently validated distributions representing the time duration typical of each individual EEI discussion during normal operations. These durations were individually built into the respective Arena module representing the appropriate EEI. Similarly, for the proposed model, our subject matter experts assisted with the generation and validation of distributions for the expected duration to accurately glean the needed EEIs from each of the reports, displays and processes proposed within the new model. In both the current and proposed model, subject matter experts validated triangular distribution parameters. Ideally, robust and quantitative work studies should be conducted with numerous real-world users on representative systems conducting realistic scenarios to gain highly accurate time measurements. The limitations of this study were such that the level of rigor and the resources needed to conduct said work studies were infeasible.

In line with the stated goals of the present research, efficiency was the sole dependent variable in question. Thus, the analysis was limited to the metric of process

efficiency (time), with the understood caveat that additional research is needed to address the system effectiveness portion of the equation.

## **Preview**

This thesis employs a scholarly format. As such, an article produced to describe and publish the research is presented in the following chapter. The article is presented as formatted for submission to the Human Factors and Ergonomics Society Journal of Cognitive Engineering and Decision Making. Because of the intent to have the article published in a public venue, the research was presented in such a way as to demonstrate its applicability to a broader audience beyond the niche of the US Air Force. As such, military vernacular and potentially sensitive data were removed. Most notably, the Air Force-unique position title of MIC was changed to the more general title of Communications Officer (CO) – though the understood roles remained unchanged. Similarly, activities and EEIs that specifically pertain to military operations were omitted or made more general. For instance, “supported units” became “customers”, “Restricted Operating Zones” (ROZs) became “clearances”, and “kill box/keypad/altitude” data became simply “location data in three dimensions”. Conversely, terms like targets, payloads and threats still hold true in civilian applications and as such were not altered. For example a real estate company employing an RPA to photograph properties would still have targeted locations, a payload of one or several cameras and potential threats including power lines (during take-off or landing phases) or known areas of electro-magnetic signal interference.

Though the research has been abstracted to a generalized level, the conclusions and resultant recommendations as discussed in the article are readily applicable across both civilian and military domains.

## II. Scholarly Article

Formatted for submission to the Journal of Cognitive Engineering and Decision Making

### **Application of Cognitive Task Analysis and Process Models to Streamline Operator Change-over**

John Machuca, Michael Miller, John Colombi, Randall Gibb

#### **Abstract**

Remotely piloted aircraft (RPAs) provide highly effective capabilities – long loiter time, detailed sensing from great distance and an expendable platform. RPAs actively support military operations, homeland defense, firefighting, search and rescue operations, geophysical surveys, and commercial surveillance. Research is ongoing to maximize the utilization of existing assets in current and future operations, up to and including the concept of simultaneous Multiple Aircraft Control (MAC) by a single aircrew. A common challenge facing both MAC and current operations is the efficient transfer of situation awareness at shift change – dubbed “change-over”. This paper details the integration of Cognitive Task Analysis, Situation Awareness Oriented Design, and discrete-event simulation to inform the design of a highly efficient user-centered change-over protocol. The resultant protocol was modeled, simulated and measured, yielding a mean duration one-third that of current methods; a highly significant result for current operations and the feasibility of MAC. The subsequent results can serve as a baseline change-over protocol.

## **Introduction**

Semi-autonomous Remotely Piloted Aircraft (RPA) have transformed the modern world, making it tremendously more accessible, surveillable, manageable and survivable for those that employ them effectively. The most powerful currency in nearly any market or endeavor, including warfare, is information – and in tactical-terms information translates directly to situation awareness (SA). The protracted RPA loiter times enable extensive and comprehensive data collection, with the end result being situation awareness the likes of which decision makers have never before enjoyed.

In the course of the last decade, leaders within the US Department of Defense (DoD), Department of Homeland Security (DHS), US Forest Service, and many other governments and commercial industries have come to recognize the power and economy that RPA technologies offer – and RPA prevalence has surged accordingly. In a 2010 federal hearing on unmanned systems and the future of war, US House of Representatives Subcommittee on National Security and Foreign Affairs Chairman John F. Tierney stated, “As the United States is engaged in two wars abroad, unmanned systems, particularly unmanned aerial vehicles, have become a centerpiece of that war effort. In recent years, the Department of Defense’s inventory has rapidly grown in size, from 167 in 2002 to over seven thousand today. Last year, for the first time, the U.S. Air Force trained more unmanned pilots than traditional fighter pilots.” (Tierney, comments made 23 March 2010)

Although the US military, more specifically the Air Force, is the best known employer of RPA technologies, they are far from the only. In 2007, NASA operated a modified Predator B to aid in firefighting efforts in southern California (GAO-08-511,

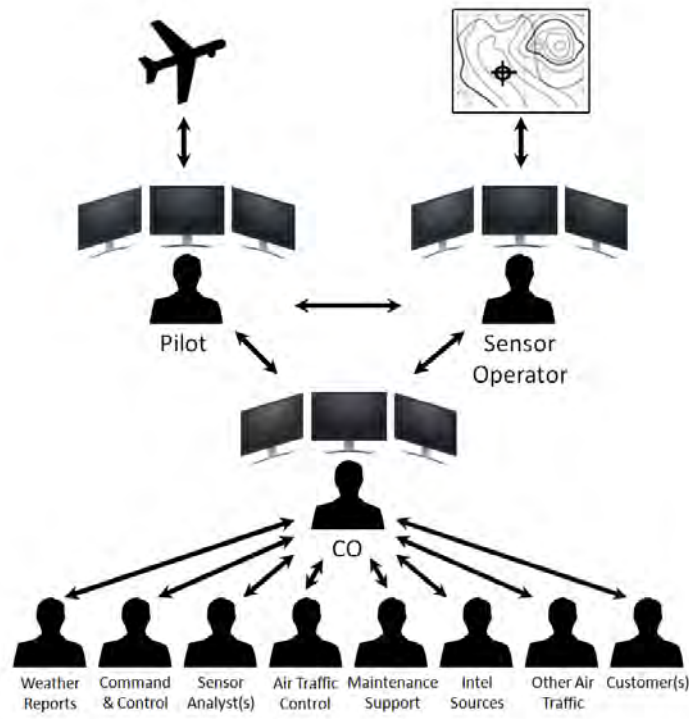
2008). In 2005, NASA, the National Oceanographic and Atmospheric Administration and industry partnered to use RPAs in the study of climate, water resource forecasting, coastal mapping and ecosystem monitoring and management. The US Department of Homeland Security Customs and Border Protection credits its RPAs with assisting agents to complete over 4,000 arrests and seizure of nearly 20,000 pounds of illegal drugs between September of 2005 and March of 2008. With renewed volcanic activity at Mount St. Helens in Washington in 2004, the US Geological Survey and Forest Service used an RPA to collect data, operating well above the heat and toxic gases of the volcano.

Commercial applications of RPAs are also being actively exploited and continuously furthered. Oil companies and geophysicists have used RPAs to more quickly and efficiently identify previously undiscovered mineral deposits by seeking out underlying rock structures via RPA-borne cesium magnetometer (magnetic field) measurements (source: <http://www.universalwing.com/technology/our-uav>). Commercial surveillance of pipelines, livestock, and roadways occurs daily. The real estate industry has employed RPAs to collect and offer detailed photography of plots of land. RPA technologies have become pervasive across numerous industries and operations, and the upward trends show no signs of slowing.

In today's fiscal environment, ample demand is not often accompanied by ample resources. And as resources become more and more constrained, RPA employers seek to utilize their existing assets as effectively as possible.

To find ways to do so, one must first understand that medium and high-altitude RPAs operate within a complex system-of-systems architecture. The complete "RPA system" typically consists of one or more air vehicles, ground control stations for both

primary mission control and take off/landing, a communications suite (including intercom, chat, radios, phones, a satellite link, etc), support equipment, and command, operations (aircrew) and maintenance crews (US Air Force MQ-1B Predator Fact Sheet, 2010) which are often distributed globally. The aircrew for these medium and high-altitude RPAs with sensor (or weapons) payloads typically consist of a two or three-person team depending on mission workload; a vehicle pilot, a sensor operator and in more dynamic applications a communications officer (CO). As one would expect, the pilot is primarily responsible for the control and operation of the physical aircraft. The sensor operator's responsibilities lie with the operation of the various sensor payloads that are installed on the aircraft. These duties, though interdependent, can task saturate the respective crewmember rapidly, particularly during a dynamic event such as targeting, active data collection or an in-flight emergency. It is during these times, ironically, that the speed, volume and relevance of communication are at the most severe. During complex operations where extensive amounts of communication takes place amongst an ever-changing number of internal and external parties, the CO (or in Air Force terms, Mission Intelligence Coordinator) acts as the aircrew's communication and global SA focal point. The MIC synthesizes, filters and passes information from and to the dozens of entities involved, thereby allowing the pilot and sensor operator to more diligently focus on their highly dynamic and cognitively taxing responsibilities.



**Figure 1. Aircrew Interaction Diagram**

***Problem Statement***

Personnel resources, particularly RPA pilots, sensor operators and communications officers, often prove to be a nontrivial limitation in today’s resource constrained environment. Thus, research is ongoing to maximize the utilization of existing personnel and hardware assets, up to and including the operational concept of simultaneous Multiple Aircraft Control (MAC) by a single aircrew. Research has identified procedural inefficiencies in current operations as well as substantial impediments to MAC including dynamic task saturation and communication challenges (Schneider & McGrogan, 2011). An identified challenge common to both current operations and MAC is the efficient transfer of situation awareness at shift change –



dubbed “change-over”. With mission durations exceeding 20 hours for medium and high-altitude RPAs, change-over is an event that often occurs more than once during any given sortie and the effectiveness, completeness and duration of the SA exchange can have immense impact on the success or failure of an on-going mission.

Past analyses have concluded that the duration of change-over activities using current protocols can consume up to 10% of an RPA pilot’s mission time in single-aircraft control (Schneider & McGrogan, 2011). In a MAC scenario, if a pilot accepts control of three or four aircraft, the subsequent transfer time and effort can rapidly balloon to consume an unreasonable percentage of the pilot’s effective mission time. Such a reduction in effective mission time runs counter to the intended objectives of MAC implementation.

Similar challenges are anticipated for the rest of the aircrew. As the communication and SA integration and dissemination focal point there are a substantial and unpredictable number of parties that the CO will interact with during the span of a given mission. Couple that with the highly dynamic nature of their mission, and it becomes clear that the effective and efficient transfer of the requisite SA data points to an on-coming CO at change-over is a significant challenge.

### ***Research Objectives***

The objective of the present research is to use pedigreed, user-centered methods to reduce the duration of time required to accomplish the transfer of sufficient SA from a losing aircrew to a gaining aircrew. Doing so could serve to increase the effective

mission availability of existing RPA forces, as well as inform the use of such methods in the creation of future protocols, including for MAC.

Furthermore, RPA industry-wide, literature does not yet exist on change-over processes and specific design recommendations despite medium and high-altitude RPAs being used in numerous civil and military applications. Similarly, a literary gap exists with respect to the operational information requirements of the RPA CO. While such analyses have been conducted on pilots, particularly in manned aircraft, no such research has been published with respect to the role of the CO. This research serves to address these gaps.

### ***Investigative Question***

The present research attempts a redesign of the RPA CO change-over protocol from the current technology-centered process to a user-centered process. The redesign is predicated upon Situation Awareness Oriented Design (SAOD) protocols and principles. The basic investigative question is, how can the current change-over process be redesigned to facilitate more expedient transfer of SA? It is hypothesized that converting the design to a user-centered design could lead to a significant reduction in process duration, thereby increasing RPA operational availability.

## **Background**

### ***Situation Awareness***

“Few issues in aviation psychology, or in the larger arena of engineering psychology, generate the controversy that is commonly associated with the topics of

mental workload and situation awareness.” (Vidulich, 2003, pp 115) Even beyond the verbiage of the definition, whether the term SA should refer to a discrete cognitive product which results from a process or to the continuously updating process itself (Flach, 1995) is a point of substantial contention.

With that in mind, the intent of this analysis is to design a brief process used to establish a sufficient “snap-shot” understanding of the operational situation, from scratch, for an in-coming aircrew member. The “snap-shot” pertains to a discrete moment in time. Thus, the system definition itself is discrete by nature and is not intended to continually update SA over time, but rather generate a relatively terse and basic comprehension. To that end, the term SA in this paper shall refer to the cognitive product which results from the processes being analyzed, as opposed to the processes themselves.

On a more practical level, at the heart of any definition of SA is the comparison between actual system status and the operator’s perception and understanding of system status (Woods, 1988). As this gap widens, SA deteriorates. As it closes, SA becomes more complete and actionable. Endsley’s definition of situation awareness has stood the test of time and follows as “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future” (Endsley, 1988, pp 792). She goes on to describe three discrete levels of SA – perception, comprehension, and projection. The first level, perception, considers the capture of critical factors or data points describing the environment. Integrating those factors into a cohesive understanding of the situation constitutes the second level of SA. The third and highest level of SA is using the information from the previous two levels to project into the future how the situation might change, thereby

enabling development of contingency plans in case of such changes. Each level of SA is progressively more difficult to attain than the previous.

Maintaining sound and complete SA is a task of paramount importance to any vehicle operator. Without sufficient understanding of one's physical surroundings, system location and orientation (in all three axes), system state of health information, the location and profile of any possible threats or allies, and so on, an operator has little to no hope of successfully completing an assigned task, or perhaps even surviving the mission. Because medium and high-altitude aircraft operate several miles above terra firma, to say maintaining sound SA is very important to an aircrew is a dramatic understatement. Any decision made during a lapse of SA, even a momentary one, can quickly result in catastrophic consequences. A review by Hartel, Smith and Prince (1991) found SA to be the leading causal factor of military aviation mishaps. Of major air carrier accidents involving human error, 88% could be attributed to SA failures per a report conducted by Endsley in 1994. These dangers are dramatically asseverated in RPA egocentric teleoperation (operator is physically removed from the vehicle and controls the craft without having line-of-sight). Physical disconnection from the system creates a host of additional SA issues for RPA crew to include lack of visual, auditory and tactile sensory cues, time lags between command issuance, vehicle response and feedback, "blind spots" in system status data, signal interruption, degradation or loss, sensor malfunctions, and system interface challenges to include the ongoing mental task of creating a fused sight picture from disparate data sources. Riley & Endsley (2005) go on to expand this list adding "out-of-the-loop syndrome", mode awareness problems, and vigilance decrements to the SA challenges faced by RPA crews.

### ***Situation Awareness Oriented Design***

Endsley et al (2003b) present Situation Awareness Oriented Design (SAOD) as a method to improve human decision-making and operational performance by enhancing the ability to maintain situation awareness. "The key is in understanding that true situation awareness only exists in the mind of the human operator. Therefore presenting a ton of data will do no good unless it is successfully transmitted, absorbed and assimilated in a timely manner by the human to form situation awareness." (Endsley et al, 2003a, pp 1)

Using SAOD, system designs are constructed with deliberate and pedigreed provisions to support efficient and effective high-level SA achievement in order to enhance an operator's decision making abilities and consequent task performance. The process begins by assessing the SA requirements involved in the task, typically by way of a CTA. Those resultant SA requirements are then translated into system design requirements.

Specifically, the process is comprised of three main facets: SA requirements analysis, SA-oriented design principles, and SA measurement.



**Figure 2. Situation Awareness Oriented Design Process**

The SA requirements analysis portion of the process addresses the task of determining what it is the operator needs to know at any given point of a task to have sufficient and operable situation awareness. SA requirements can be further defined as

the requisite dynamic information data points (as opposed to static knowledge such as rules, policies, etc) that an operator would need in order to achieve all goals and sub-goals of their task(s), often referred to as essential elements of information (EEIs). It is important to note that this analysis is not strictly limited to identifying the individual dynamic data points, but may also need to include careful consideration for how that information is presented and integrated when making a decision. The tool of choice to accomplish this phase of the analysis is typically an appropriate form of Cognitive Task Analysis (CTA), which is detailed in the next section.

The crux of SAOD is taking the products from the SA requirements analysis portion of the process and then applying the fifty SA-Oriented Design principles (Endsley et al, 2003b) which were developed based upon a theoretical model of the methods used in acquiring and maintaining SA in dynamic complex systems. The guidelines are "focused on a model of human cognition involving dynamic switching between goal-driven and data-driven processing and feature support for limited operator resources" (Endsley et al, 2003a, pp 2). Topics addressed in the heuristics include, but are not limited to, supporting SA in multi-warfighter and distributed team environments, design of alarms, dealing with the complexity of systems, design of advanced automation concepts, and so on. A sampling of the individual principles includes:

Principle 1 - Goal oriented information displays should be provided and organized so that the information needed for a particular goal is co-located and directly answers the major decisions associated with the goal.

Principle 3 - Whenever possible provide direct presentation of higher-level SA needs (comprehension and projection activities) as opposed to simply providing low order data for the operators to integrate and interpret themselves.

Principle 23 – Provide consistency and standardization on controls across different displays and systems.

Principle 35 – Use automation for assistance in carrying out routine actions rather than higher level cognitive tasks.

Principle 47 – Provide flexibility to support shared SA across functions.

For a full list of the SAOD principles, see Endsley, Bolte and Jones (2003b).

The generic nature of the principles and heuristics ensures the universal applicability of SAOD to any system design where SA plays a role. Clearly, every principle will not be applicable to every system design, but typically a multitude of the principles will. The flexibility and pedigree of the SAOD principles has been explicitly demonstrated by successful application in the fields of remote maintenance operations, medicine, manufacturing, and military command and control.

The SA Design measurement phase of the SAOD process is where direct or indirect measurement of SA is attempted to gauge success of the effort and the potential for further design improvements. Recommended SA measurement methods include the indirect methods of verbal protocols, communication analyses, psychophysiological metrics, behavioral measures, and performance outcome measures. Direct measurement methods include self-ratings, Situational Awareness Rating Technique (SART) (see Taylor, 1990), observer ratings, post-test questionnaires, on-line real-time questionnaires

and the Situation Awareness Global Assessment Technique (SAGAT) (see Endsley, 1988).

These methods attempt to measure the effectiveness of a SA system design. In a departure from typical SAOD protocols, the present research takes for granted the effectiveness of the system due to the proven and validated pedigree of the EEIs and focuses on the efficiency of the design in a specific attempt to minimize the expected process duration. To measure this dependent variable, statistical analysis was accomplished on the output of discrete-event simulations conducted within Rockwell Automation's Arena Simulation Software.

### *Cognitive Task Analysis*

Borne of the applied psychology field, cognitive task analysis is a broadly applied and often customized kit of tools and techniques used for the identification and description of the knowledge and strategies needed for task accomplishment. Per Shraagen et al (2000, pp 3), "Cognitive task analysis is the extension of traditional task analysis techniques to yield information about the knowledge, thought processes, and goal structures that underlie observable task performance." While CTA has numerous manifestations, structures and levels of formality, typically the process can be described as five steps which are briefly detailed in the following paragraphs.

At the outset of a CTA, preliminary data collection should be accomplished. The intention of this first step is for the analyst to become familiarized with the domain and process being studied and includes the identification of key cognitive tasks, with particular attention paid to those tasks that are difficult, frequent or highly critical



cognitive tasks within the job. To achieve these ends, the tools and techniques at the analyst's disposal include literature review, observations and unstructured interviews. At the conclusion of this effort it is generally beneficial to visually depict any results, often in the form of knowledge or concept maps describing the specific information requirements, EEIs, and any relevant relationships between tasks and subtasks. The creation of such knowledge representations comprises the second step of the procedure.

With education of the domain, the process and its tasks attained and represented, the analyst can then begin the third step of a more intelligent and focused investigation of the EEIs by implementing applied knowledge elicitation methods which include interviews, both unstructured and structured, verbal protocol walkthroughs and the Critical Decision Method (see Klein et al for additional information on the Critical Decision Method). Of these, structured and unstructured interviews are most commonly selected as they require little training and are relatively easy to employ and customize to the desired level of investigative formality.

Next the analyst must take the information that has been collected thus far and synthesize it into meaningful conclusions. As part of this fourth step, the resultant data should be refined, packaged and presented in an intuitive way to facilitate taking the synthesized information and conclusions and providing it to subject matter experts to have the data verified for its intended purpose. With the data and resultant conclusions validated, the yield of actionable information to inform intelligent system design will have been delivered.

The fifth and final step of the CTA is to take the achieved results and to translate them into meaningful and informative models which should “reveal the underlying skills,

mental models, and problem-solving strategies used by experts when performing highly complex tasks” (Clark et al, 2008, pp 582). These models can then be used to inform curriculum, training procedures and system design.

### *Change-over*

Lacking a well-defined industry standard change-over protocol, this study used US Air Force protocols as the baseline. The US Air Force has one of the most robust, mature and heavily utilized change-over procedures in the industry. Furthermore, the Air Force is actively grappling with the economic constraints previously discussed as the impetus of the research and is actively seeking out methods to maintain or even increase operational capabilities while simultaneously reducing resources including manpower. A general change-over protocol, as documented by visits and interviews conducted with RPA operators, was selected to serve as the baseline for this analysis. No single person or specific organization’s protocol was selected. Rather, to account for variation as well as to reduce the sensitivity of the information, the process was generalized to capture only the ubiquitous characteristics that are relevant across all medium and high-altitude RPA operations, both federal and civilian.

Some US Air Force RPAs have sustainable loiter times greater than 20 hours (Chappelle et al, 2010). Therefore, operational RPA squadrons typically operate multiple shifts to provide the necessary aircrew coverage. As such, change-overs, being defined as the procedural transfer of situation awareness and RPA control from a losing crew to a gaining crew, are a common occurrence that often takes place multiple times during the course of any given RPA tasking.

In terms of duration and therefore operational impact, analysis has shown that change-overs can account for 8-20% of total mission time in single aircraft control, and have been projected to take up to 40% of total mission time if a MAC of four were employed (Schneider & McGrogan, 2011). Furthermore, several military RPA mishaps have been attributed to failures either during or as the result of a change-over (Tvaryanas et al, 2005). These analyses aptly highlight the challenge that efficient and effective change-over presents to modern RPA operations.

It is important to note that during these change-over periods the attention of the out-going crew is split amongst conducting change-over discussions with the in-coming crew and continued support of the ongoing taskings. As such, all reasonable efforts are made to avoid conducting change-over during any dynamic situation such as an in-flight emergency, targeting, signal or optical collections, weapons employment, and so on.

The baseline RPA change-over process in this report is detailed as three distinct phases: the in-coming aircrews receive a mass pre-mission brief from the mission support cell, each individual oncoming crew member receives their individualized change-over briefs from their respective losing crew member within the ground control station, and finally the members of a gaining crew complete an internal crew brief to establish plans of action.

Phase 1 – Gaining crew receives pre-mission brief from mission support cell

Approximately 30 minutes prior to the scheduled change-over time, the mission support cell provides the gaining crew with a pre-mission brief to educate them on pertinent mission data (mission assignment, intelligence reports, weather reports, etc),

rules of engagement and recent mission developments. This step is intended to provide the on-coming crew with macro-level SA prior to progressing to subsequent steps.

Generalized, this phase provides context and top-level strategy data. For example in a commercial topographic cartography mission, the crew would be informed of the target area to be mapped, the desired image types and fidelities and so on.

#### Phase 2 – Change-over brief

This step is where the bulk of SA information is exchanged. Typically, the losing CO utilizes electronic or hardcopy checklists, handwritten flight logs/notes and current system displays to provide a verbal brief of all relevant mission and vehicle data. Topics discussed include weather, airspace data, datalink information, emergency mission information, and target information. The authority to declare this step complete resides with the gaining CO. This prevents the losing CO from departing the area until the gaining has self-declared satisfactory operational situation awareness.

Generalizing, this step focuses on tactical-level information. Recalling the example cartography mission, this would include current equipment (payload) status and configuration information, information on pertinent relationships with external parties, system maintenance issues or anomalies, detailed target data and so on.

#### Phase 3 – Gaining crew conducts crew brief

With the new crew in their seats and in control of the aircraft, an internal crew brief is conducted. During this time, the crew discusses key items of interest identified in previous steps and protocols of internal task allocation termed “contracts”. These

contracts are typically the pilot's directions to the other crew members on how he or she would like things to operate, as the pilot is typically the team lead. For instance, in case of an in-flight emergency, the pilot may wish to allocate responsibility for all communication with external parties to the CO to enable the rest of the crew to focus entirely on the dynamic task at hand. Another common contract put in place is for all textual communication to occur in a designated chat room visible to all, as opposed to permitting "whispers", which are chat rooms established from one party directly to another so as to have information passed out of view from uninvolved parties. A pilot can establish crew contracts as he sees fit and does so to create clear ground rules with respect to how the crew shall conduct business. These contracts in and of themselves have dramatic impact on the crew's team SA and often are directly pertinent to the key elements of information each crew member needs to keep track of to maintain satisfactory operational shared SA. With contracts in place and a baseline of team SA established the change-over process is declared complete.

In a general application, this final step is comparable to the designated crew lead (typically the pilot or a shift manager) providing final direction with respect to phase 1 (strategy and context) and phase 2 (system and target status) information.

## **Methodology**

### *Overview*

To achieve the stated research objectives the present research employed Cognitive Task Analysis (CTA) to identify a comprehensive list of the root information COs require to achieve operational SA during change-over, which were then leveraged against the

Situation Awareness Oriented Design (SAOD) principles to facilitate pedigreed improvement to the system's architecture keeping the overall user-centered goal of timely and effective SA transfer in mind. In line with the focus of the research, but in contrast to typical SAOD measurement methods, the resulting framework was modeled and measured via discrete-event simulation. Finally, the simulation results were compared to paired data from the current design and conclusions were drawn.

***Step 1. Cognitive Task Analysis of current change-over process***

Cognitive Task Analysis was employed to dissect and catalog the knowledge elements that must be exchanged at change-over in order for the receiving CO to be able to achieve sufficiently operational SA.

The preliminary data collection phase of the CTA was accomplished via robust literature review on the topic of RPA team operations followed by unstructured interviews and operational observations of active US Air Force COs. Knowledge representations were created to describe the tasks, subtasks and information requirements observed. These representations facilitated the third CTA step of conducting formalized in-depth interviews and operational observations of COs to form a solid understanding of the change-over process. In this step the root essential elements of information, EEIs, or the lowest-level bits of information needed for a CO to achieve operational situation awareness, were identified and explored. These EEIs were then traced in two fashions – chronologically, in that they were each allocated to their appropriate time-ordered step(s) of the current process, and by user-centered goals in that each EEI was allocated to the higher level task it supports, which in turn were rolled-up to the overarching user

operational goals that those tasks serve. The top-level CO goals identified were to facilitate aviation (keeping the RPA airborne), navigation, communication, finding the target, fixing on the target (locking sensors on to the target), tracking the target, targeting the target with the appropriate sensors, engaging the target (making a collection or in the military realm employing ordinance), and assessing the results. By tracing EEIs to chronological steps as well as user tasks and goals, any missing, redundant, sequentially “misplaced” or non-value added EEIs are highlighted informing subsequent analyses.

In the final step of the CTA, the data and results of the process were packaged and presented to the RPA subject matter experts for validation and verification. The subject matter experts were active communications officers (Air Force MICs) and were equally split amongst officer and enlisted members with flight qualifications equally divided amongst MQ-1 Predator and MQ-9 Reaper aircraft. US Air Force active duty, reservists, and Air National Guard components were each represented.

### ***Step 2. Creation of current process architecture model***

With the CTA completed, a robust and detailed understanding of the current change-over process was achieved and a model built. Rockwell Automation’s Arena Software, a graphical discrete-event simulation tool, was used to build and analyze the models. Both the current and proposed models were constructed with a chronological flow of the EEIs as addressed during the change-over process. In other words, the outgoing CO would begin the process at the “Start” module in the model, and progress along a singular path addressing each EEI in order, concluding the process upon arrival to the “Finish” module.

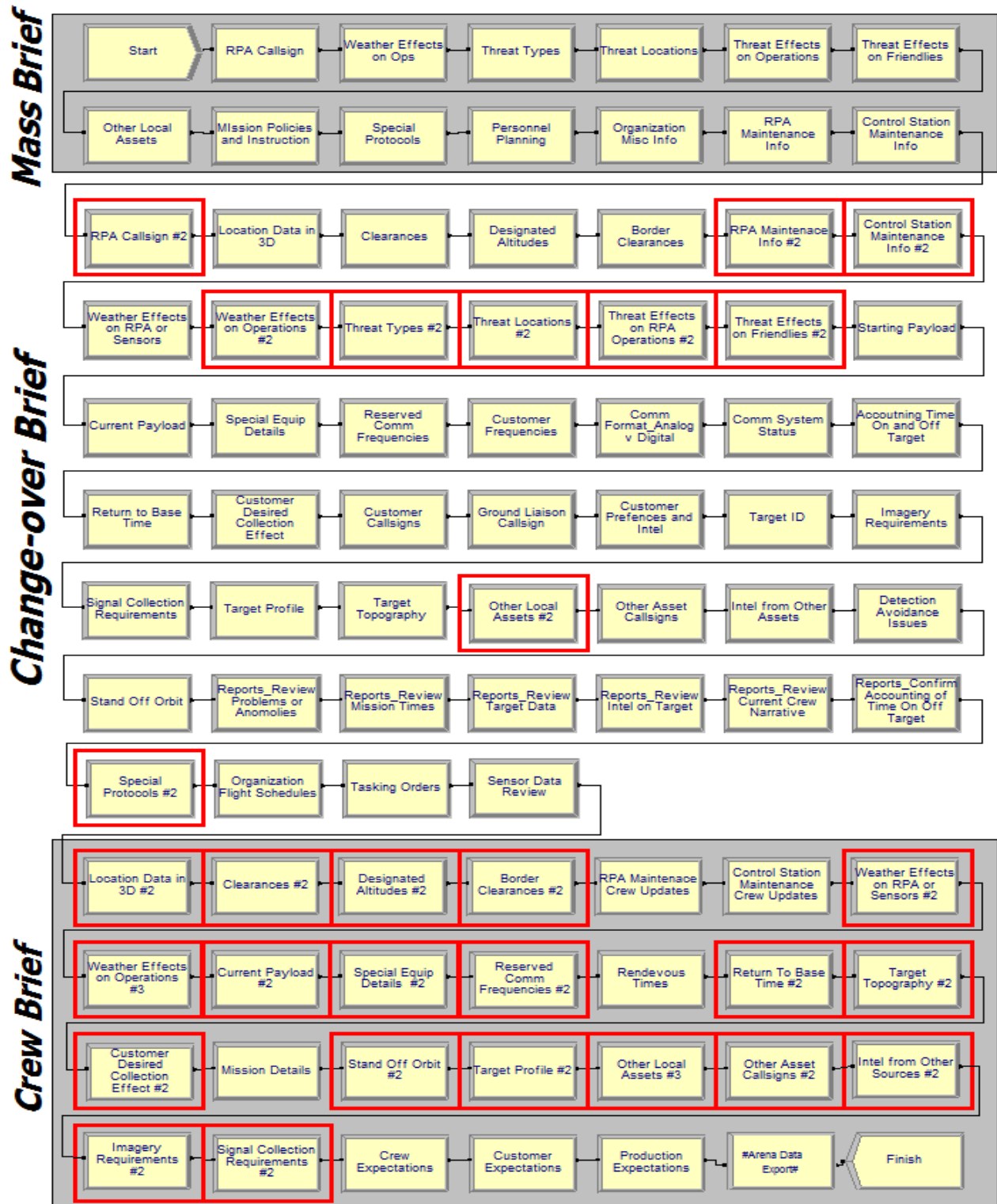


Figure 3. Current Change-over Process Arena Model



Depicted within the model the segregated phases of the process - mass brief, change-over brief and crew brief, can be seen. Also, individual EEIs that are repeated (addressed at least once prior in the model) are outlined in an unshaded box to clearly depict the amount of redundancy in the current process. With that said, undoubtedly redundancy is often both beneficial and intentional. Redundancy is often used as a method to reinforce key information, provide opportunity for updates to dynamic information, or confirm that multiple parties have the same sight picture throughout an exchange. With the identification of substantial EEI redundancy in the current process, a request was put to the subject matter experts to point out any EEIs for which redundancy could be justifiably beneficial. Only the EEIs pertaining to weather were identified as advisable to revisit with time. The operational implications of weather are dramatic and weather systems in many parts of the world can change rapidly. The duration of the current process creates the need to revisit this topic. The repetition of all other EEIs identified as redundant were considered to be non-value added tasks.

### ***Step 3. Application of Situation Awareness Oriented Design principles***

With the CTA accomplished and root EEIs identified, the SA requirements were translated into system design requirements. The building blocks of the new process were now in hand. To facilitate disciplined and pedigreed design of the new process using these building blocks, the principles and protocols of SAOD were brought to bear. While nearly all of the 50 principles informed the design in some way, the following is a brief discussion of the five SAOD principles that offered the greatest relevance and impact to this analysis.

Principle 1 - Organize information around goals. This principle asserts that the operator's major goals constitute the framework around which all information requirements and activities should be centered. Often, this is not the case and information is presented based entirely upon the sensor or system creating the data (e.g., fuel level, oil temperature). "Information should be organized so that the information needed for a particular goal is co-located and directly answer the major decisions associated with the goal." (Endsley et al, 2003b, pp 83) To this end, the goals identified during the CTA process became the focal points to which the various EEIs were allocated.

Principle 2 - Present level 2 information directly – support comprehension. "As attention and working memory are limited, the degree to which displays provide information that is processed and integrated in terms of level 2 SA requirements will positively impact SA." (Endsley et al, 2003b, pp 83) For example, it is much more intuitive to directly display the difference between actual airspeed and required airspeed given the current climb angle, as opposed to simply stating the current airspeed and expecting the operator to "do the math." This principle was particularly applicable while determining the method of presentation to be used to convey certain EEIs. For example, it was determined to be more useful to display details such as the aircraft's required stand-off orbit from a given target visually in a geographical display as opposed to via verbal protocols.

Principle 3 - Provide assistance for level 3 SA projections. Similar to the previous principle, this heuristic reduces the level of cognitive effort required on the part of the operator to go from a lower-level understanding of current states to an integrated mental model predicting future states and trends. Trend graphs and the like facilitate an

operator's ability to forecast what may be down the road. Offering time-phased data in a clear manner, such as a graphical display, has much greater utility than a simple snap shot capturing only current status, as you would likely receive from a terse verbal statement on the matter.

Principle 39 - Make modes and system states salient. System states and modes are pivotal pieces of information that can be the difference between a given data point being within normal bounds or being a sign of imminent danger. Mode confusion is a common problem when directly operating nearly any vehicle and the issue is tremendously asseverated in egocentric teleoperation of an aircraft. Thus, diligent effort was made throughout this analysis to provide for presenting system states and modes as saliently as possible. The primary instantiation of this principle in the improved process has been dubbed the RPA Data Display. This display directly illustrates key EEIs pertaining to the state of the air vehicle and the ground control station – aircraft starting and current payload, for example. To convey these EEIs, the envisioned display depicts a silhouette of the RPA with the starting payload shown on each of the respective pylons. If ordinance were dropped during the mission, the ordinance's image on the respective pylon would go from a stark solid filled image to a shaded silhouette. Such an image would make it so that in a brief glance one could quickly understand what payload the aircraft took off with, currently has, and even some information on potential weight/balance implications that may come with a change in payload symmetry across the mission.

Principle 45 - Build a common picture to support team operations. Obviously, the MIC is only one part of the aircrew team. And the MIC's change-over EEIs are not the same as those for the pilot or sensor operator. Thus, when it comes to SA needs, one size

does not fit all. So the change-over process as designed here is not intended to be precisely replicated and applied to the pilot and sensor operator's change-over processes (nor as absolute truth across all industries – some degree of customization may be necessary). However, the overlap of the EEIs that are common amongst the team members (and industries) is nontrivial, and value can be derived from developing systems that facilitate a common sight picture by creating a common data source for at least a subset of the SA information each crew member needs. In the improved design this principle is demonstrated by the Mission Data Report, the Geospatial Display and the RPA Data Display. These data sources contain information that the entire team needs to be aware of. Mission details including target information, desired collection or engagement affects, rules of engagement, intelligence reports, and area threats will be contained in the Mission Data Report and all members of the team would count these pieces of information amongst their respective change-over EEIs. Similarly, the entire crew will need at least a basic geospatial awareness of where the aircraft is, where the target is, the intended stand-off orbit from the target given a particular detection concern, what airspace clearances do they have, where the threats are, and where each of those data points are with respect to one another. Thus a common display that can be reviewed by all members of the aircrew would do well to facilitate a common sight picture of geospatial SA.

#### ***Step 4. Creation of the new process model***

Analyzing the identified EEIs in light of the SAOD principles, weaknesses of the current change-over system are highlighted and methods to improve the process, by

focusing the design on the overarching goal of SA exchange and formation, are realized. Using the principles, especially those discussed above, it became clear that an improved CO change-over system should incorporate generated textual reports for relatively static mission information, intuitive visual displays of all geospatial information, and salient system displays depicting dynamic system modes and states. The current change-over protocol is technology-centered in that it has the relevant EEIs for these portions of overall SA scattered throughout the process. This is largely because the data is grouped and reviewed according to its respective technology. This results in an unintuitive and nonintegrated presentation of the data, inhibiting level 2 and 3 SA formation. SAOD principles point out the value of arranging such a process around the user's overarching goals and tasks so as to expedite level 2 and 3 SA achievement. Rectifying these issues and the elimination of non-value added tasks has yielded the following change-over system definition.

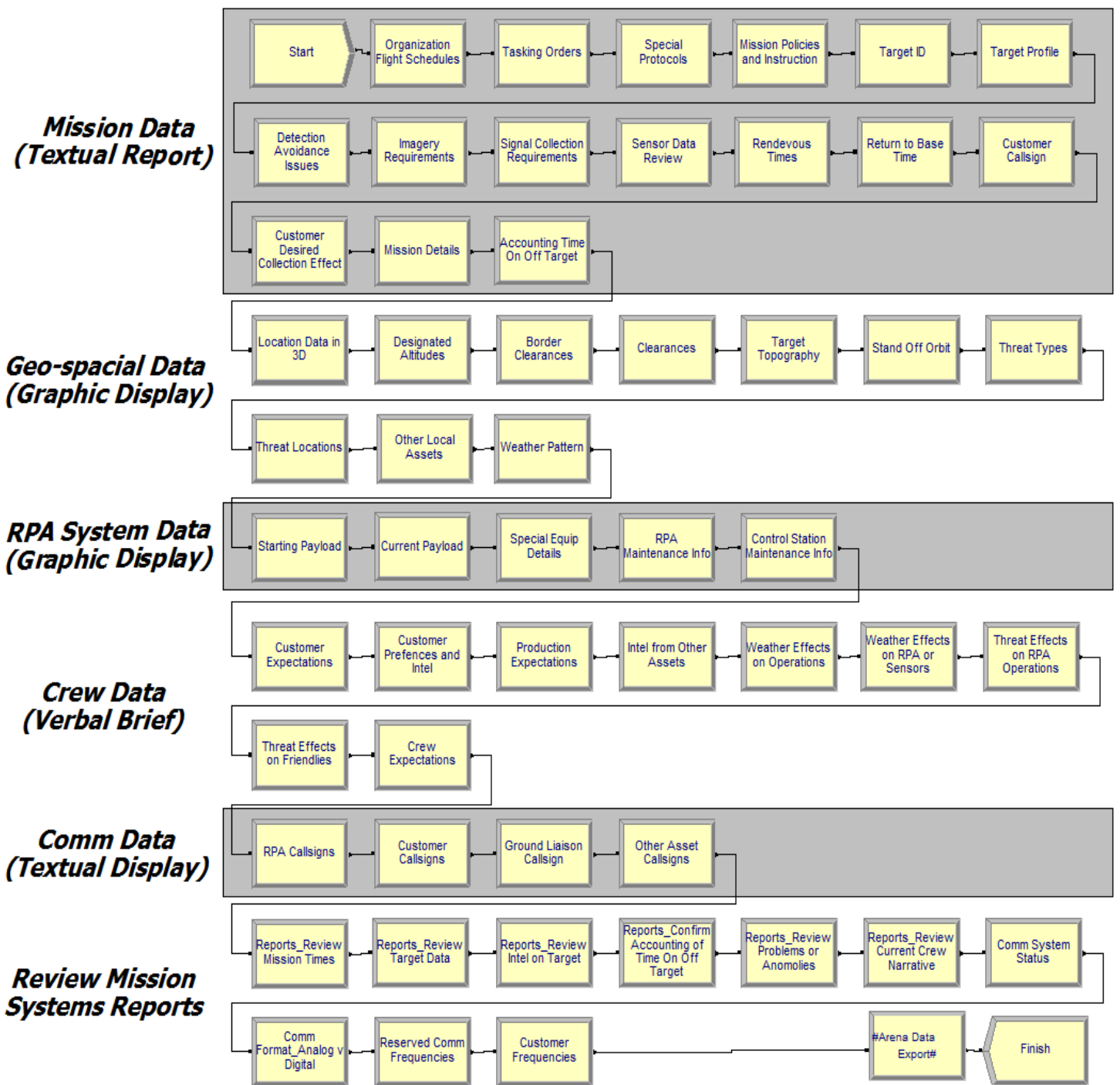


Figure 4. Proposed Change-over Process Arena Model

Not all of the change-over EEIs are ideally expressed by way of a generated report or visual display, as found in the mission data report, geo-spacial display or RPA system data display. These EEIs are often nuanced, difficult to quantify and even subjective in nature at times. With this sort of information two-way discussion is often required to ensure clarity and understanding. The last three portions of the proposed process account for these sorts of EEIs. These steps are intended to be carried out face-to-face in the ground control station between the losing and gaining COs. These three data collections are the only portions of the proposed design where the losing CO's efforts must be split amongst the change-over process, and continued support of an on-going sortie. The first three steps can be accomplished by the gaining CO outside of the ground control station independent of the losing CO provided the reports and displays are made available.

***Step 5. Statistical analysis of current and proposed model output***

In line with the SAOD process described previously, the third phase of the process, SA measurement, was conducted. To accomplish this step in accordance with typical SAOD guidelines, representative systems and interfaces would be built, realistic and diverse scenarios developed and experienced operators would conduct trials for accurate SA measurements to be taken. With that said, the typical methods of SA measurement mentioned previously (psychophysiological metrics, SART, SAGAT) are intended to measure the effectiveness (accuracy and completeness) of SA generation and maintenance. Rather, the focus of the present research is placed squarely on the efficiency (time duration being the sole metric) of the methods.

The method selected to measure and analyze the efficiency of the processes was Monte Carlo discrete-event simulation. For the current model, subject matter experts provided input and subsequently validated distributions for the duration of each individual EEI related task. These durations were individually captured in the respective model. For the proposed model, our subject matter experts assisted with the generation of and subsequently validated triangular distributions for the expected duration to accurately collect the needed EEIs from each of the reports, displays and processes in the proposed model. Statistical analyses of the results were conducted on the output from Arena for each of 500 replications for both baseline and proposed models using synchronized random number seeds.

### **Assumptions and Limitations**

In both the current and proposed model, the subject matter expert validated triangular distribution duration estimations for the EEIs were at best, estimations. This presents an admitted shortcoming of the analysis. Ideally, robust and quantitative work studies should be conducted with numerous real-world users on representative systems conducting highly realistic scenarios to gain highly accurate time measurements. The limitations of this study were such that the level of rigor and the resources needed to conduct said work studies were infeasible.

In line with the stated goals of the present research, analysis was limited to process efficiency (time), with the understood caveat that additional research is needed to address the system effectiveness portion of the equation. Clearly, the effectiveness as well as the efficiency of any system must be considered to make an accurate and fully

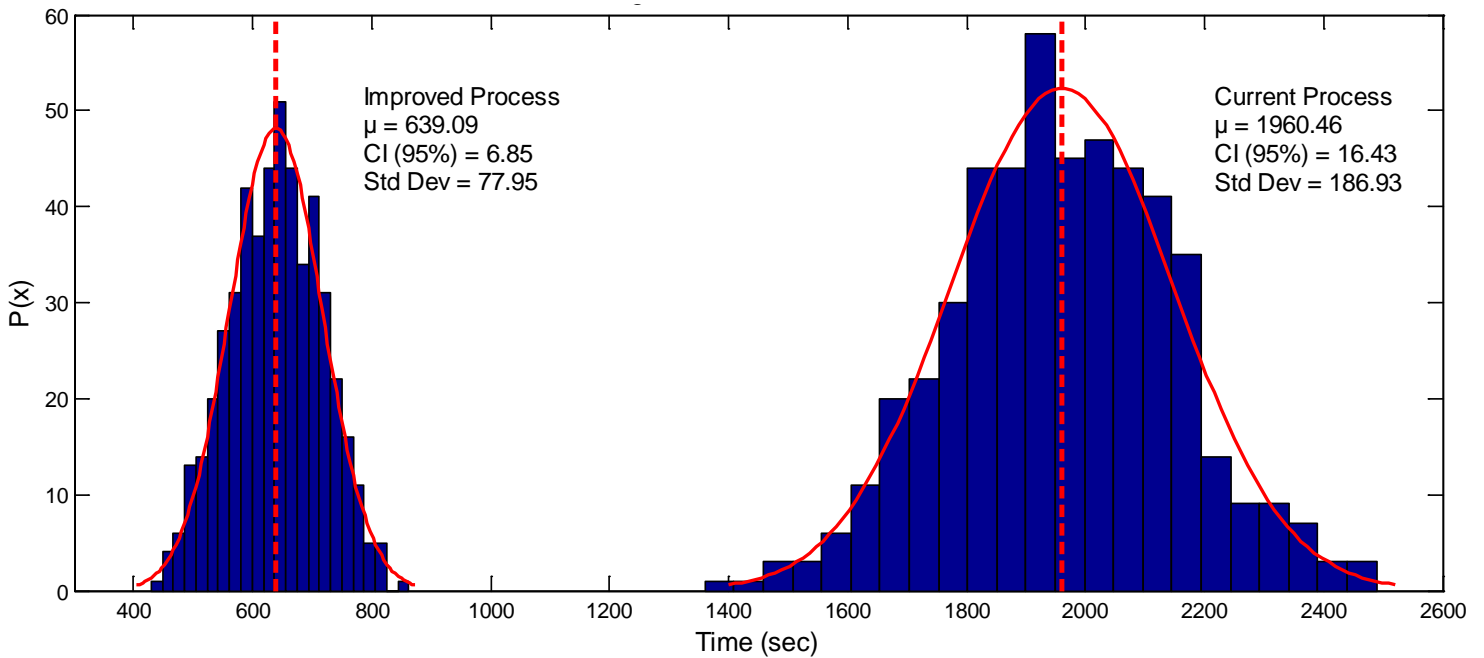


informed decision on whether a design truly offers valuable improvements, or is even acceptable for use. However in this case, efficiency was the sole dependent variable in question.

Part of the motive for this analysis was to diminish the obstacle that change-over poses to MAC implementation. However, this analysis was performed solely on single aircraft control systems. While logical arguments can assert that lessons learned presently will be able to directly inform highly efficient MAC change-over process design, a robust analysis on true MAC implications is warranted.

## **Results**

For the current change-over process a mean duration time of 1960 seconds (32.67 minutes) with a standard deviation of 187 seconds and a 95% confidence interval of  $\pm 16$  seconds was calculated. For the proposed process, a mean duration time of 639 seconds (10.65 minutes) with a standard deviation of 78 seconds and a 95% confidence interval of  $\pm 7$  seconds were calculated, yielding a mean difference between the models of 1321 seconds (22.02 minutes) with a standard deviation of 202 seconds. Conducting a paired t-test, the mean reduction in process duration was proven to be significantly greater than zero;  $t(499) = 2.4$ , one-tail  $p = 0.009$ . A 95% confidence interval about the reduction in total process duration comes out to be (1339, 1303) seconds.



**Figure 5. CO Change-over Process Duration PDFs**

## Conclusion

The overarching goal of the effort was to increase RPA mission effectiveness by way of providing crews with a faster method to transfer SA at change-over. An additional intent was to have the resultant protocol be industry-independent and to serve as a change-over process baseline. To do this, careful consideration had to be paid in determining the precise data points that must be exchanged for the recipient to have sound and operationally actionable SA on the system and its context. With those data identified, a sound understanding of pedigree, user-centered principles proven to facilitate the generation and maintenance of situation awareness fostered dramatic clarity and insight into potential system improvements. The results of the calculations performed to measure the forecasted improvements of the proposed system were decisive and unambiguous – with this study’s proposed change-over protocol a 67.4% estimated reduction in the time required to accomplish change-over could be possible for AF assets.

Conclusions such as these are relevant, timely, and powerful across all RPA industries, but now require operational validation.

The power of the results of this analysis lie in the potential to increase RPA mission effectiveness and availability in single aircraft control by reducing the time burden placed on current assets during change-over, as well as serving to dissolve some of the barrier that SA transfer poses to the feasibility of MAC implementation. However, it is well worth noting that the findings of is effort have valuable relevance beyond the aviation industry. For instance in the medical field, doctors and nurses must conduct change-over processes to relinquish and assume responsibility for patients. Additional applications include industries such as nuclear operations, chemical manufacturers, and chemical users with processes times that span several shifts.

Additionally, no CTA-based research has yet been published on the RPA CO role or on change-over protocol design despite their criticality to the success of RPA missions. This report addresses those gaps.

Furthermore, the synergistic coupling of SAOD and discrete-event simulation to specifically measure the efficiency of a resultant design as opposed to the effectiveness of the design is novel and this work represents the first known publicized demonstration of such a tactic.

### **Future Research**

While the proposed system put forth by this analysis asserts clear and demonstrated improvements, further and more rigorous analyses are needed to fully vet designs and further optimize features. Particular areas of future research include an in-

depth quantitative analysis of both the current and proposed system design task times to calibrate the here-in surmised duration triangular distributions for each EEI. Also, as previously mentioned, the current analysis measured and drew conclusions on the efficiency of the processes being considered. Due diligence must also be paid in analyzing the effectiveness of the systems before final actionable conclusions should be drawn. Furthermore, a robust analysis of this study's true implications to the MAC change-over process is called for.

On a larger note, in terms of researching SA with respect to RPA operations, greater emphasis must be placed on the role of the CO. While the pilot, and to a lesser extent the sensor operator roles have received moderate study (see Schneider & McGrogan, 2011; Chappelle et al, 2010; Ouma et al, 2011), little has been done with a focus on the CO position despite its criticality to complex operations. It should be understood that the paradigm stemming from manned aircraft of the pilot having the most critical SA needs does not typically hold in modern egocentric medium and high-altitude RPA operations. At best, SA needs are shared equally amongst the crew and at worst, the pilot may in fact have a less substantial SA acquisition and maintenance challenge than the communications officer. To prevent the focus of future research from being mismatched, or even largely misplaced, a great deal more research is needed to better understand the significance and challenges of the communications officer role in current and future RPA operations.

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**Appendix A. Example knowledge representation of current process chronological**

**CTA data**

| Task # | Activity | Info Type   | Info                     | EEI                 | EEI Label |
|--------|----------|-------------|--------------------------|---------------------|-----------|
| -      | CO Brief |             |                          |                     |           |
| -      |          | Msn details |                          |                     |           |
| 51     |          |             | Msn schedules (RSTA/ATO) | Return to base time | MS10      |
| 52     |          |             | Customer                 | Customer unit       | MS1       |
| 53     |          |             |                          | Customer intel      | MS8       |
| 54     |          | RPA data    | Payload                  | Starting weapons    | RP4       |
| 55     |          |             |                          | Current weapons     | RP5       |
| 56     |          |             | Anomalies                | RPA mx issues       | RP9       |

**Appendix B. Example knowledge representation of goal-based CTA data**

Note the traceability to current process chronological representation via EEI label

| EEI Label | Category - goal | Step              | Topic           | Info       | EEI Name                  |
|-----------|-----------------|-------------------|-----------------|------------|---------------------------|
| RP9       | RPA - aviate    | Change-over       | Mission Details | Mx updates | RPA mx updates            |
| RP9       | RPA - aviate    | Mass Brief        | Squadron Info   | Mx updates | RPA mx updates            |
| RP8       | RPA - aviate    | Change-over       | Mission Details | Mx updates | GCS mx updates            |
| MS7.2     | MS SYS - comm   | Change-over Brief | Workstation     | Skynet     | Review Time on/off target |
| TH1       | GEO - nav       | Mass Brief        | Mission Details | Threats    | Threat Types              |
| TH1       | GEO - nav       | Change-over       | Mission Details | Threats    | Threat Types              |



## **Appendix C. Scholarly Article - Allocation of Communications to Reduce Mental Workload**

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### **Abstract**

As the United States Department of Defense continues to increase the number of Remotely Piloted Aircraft (RPA) operations overseas, improved Human Systems Integration becomes increasingly important. Manpower limitations have motivated the investigation of Multiple Aircraft Control (MAC) configurations where a single pilot controls multiple RPAs simultaneously. Previous research has indicated that frequent, unpredictable, and oftentimes overwhelming, volumes of communication events can produce unmanageable levels of system induced workload for MAC pilots. Existing human computer interface design includes both visual information with typed responses, which conflict with numerous other visual tasks the pilot performs, and auditory information that is provided through multiple audio devices with speech response. This paper extends previous discrete event workload models of pilot activities flying multiple aircraft. Specifically, we examine statically reallocating communication modality with the goal to reduce and minimize the overall pilot cognitive workload. The analysis investigates the impact of various communication reallocations on predicted pilot workload, measured by the percent of time workload is over a saturation threshold.

## **Introduction**

Over the past several decades, the US Air Force has harnessed and exploited the immense tactical power that middle and high-altitude Remotely Piloted Aircraft (RPAs) bring to the battlefield. As a consequence, the demand for RPA operational support continues to increase. It is important to realize that RPAs are part of a complex system. The system has many components including one or more air vehicles, ground control stations for both primary mission control and takeoff/landing, a suite of communications (including intercom, chat, radios, phones, a satellite link, etc), support equipment, and operations and maintenance crews [1]. Assets and requisite resources to support those operations are limited and personnel resources, particularly RPA pilots, often prove a nontrivial constraint. This inevitably leads innovators to seek out RPA force-multiplying efficiencies to assist in bridging the resource/demand gap. One such efficiency being pursued is simultaneous control of multiple aircraft by a single pilot, or Multi Aircraft Control (MAC). This concept of operations has been documented in the US Air Force UAV flight Plan [2].which calls for future systems in which a single pilot will simultaneously control multiple RPAs to enable increased aerial surveillance without increasing pilot manpower requirements. Previous research on the cognitive workload experienced by pilots during MAC indicated that frequent, unpredictable, and oftentimes overwhelming volumes of communication events can produce unmanageable levels of system induced workload for MAC pilots [3]. To further investigate this identified problem, our study makes use of IMPRINT Pro, a Multiple Resource Theory (MRT) based dynamic, stochastic simulation to analyze impacts to cognitive workload by a disciplined communication modality reallocation construct.

## **Background**

In the RPA domain, communication is a continuous and demanding process. Crews must track, at a minimum, information regarding weather, threats, mission tasking, mission coordination, target coordination, airspace coordination, fleet management, and status and location of any friendly units. The RPA pilot is not only responsible for aircraft control but is also a critical member in a multi-path communications infrastructure [4]. In the ground station, communication with the pilot takes place in one of two modalities: textual chat window(s) or the speech-based radio systems. At any given moment, a pilot may need to monitor multiple chat windows and listen to numerous parties operate over the radio. The multitude of communication sources and different media coupled with the quick inter-arrival rate of these events during a dynamic scenario drives an incredible cognitive workload for the pilot.

Cognitive or mental workload expresses the task demands placed on an operator [5]. Calculation of task demand, or task load, often considers the goals of the operator, the time available to perform the tasks necessary to accomplish the goals, and the performance level of the operator [6]. Therefore, workload increases when the number or difficulty of tasks necessary to perform a goal increase, or when the times allotted to complete these tasks decrease. Assuming that the operator has a limited amount of mental resources (e.g., attention, memory, etc.) that he or she can utilize to complete the necessary tasks, mental workload corresponds to the proportion of the operator's mental resources demanded by a task or set of tasks. Several methods have been employed to measure and quantify mental workload over the past four decades and have been summarized in numerous publications [5,7,8]. The current analysis incorporates Multiple

Resource Theory (MRT) into the workload calculations to account for channel conflict driven workload.

As a theory, MRT purports the existence of four mental dimensions (or channels) available to process information and perform tasks. The dimensions include processing stages, processing codes, perceptual modalities and visual channels. These channels are allocated to concurrent tasks with the difficulty of the tasks and the demand conflict between channels driving the overall mental workload value [9]. MRT accurately describes the concurrent nature of tasks imposed on an RPA pilot (performing primary tasks while communicating and monitoring communication) and is therefore an appropriate theory to apply to the present analysis.

## **Method**

Therefore, the specific channels employed by the modeled communication events are highly relevant to the MRT workload calculations. As communication events begin to conflict with existing work activities on the various channels, the calculated overall cognitive workload will account for such conflicts. This construct enables the analysis to address the question of whether or not adjusting the intentional allocation of communication events to particular modalities will be able to meaningfully affect overall cognitive workload.

## ***Model***

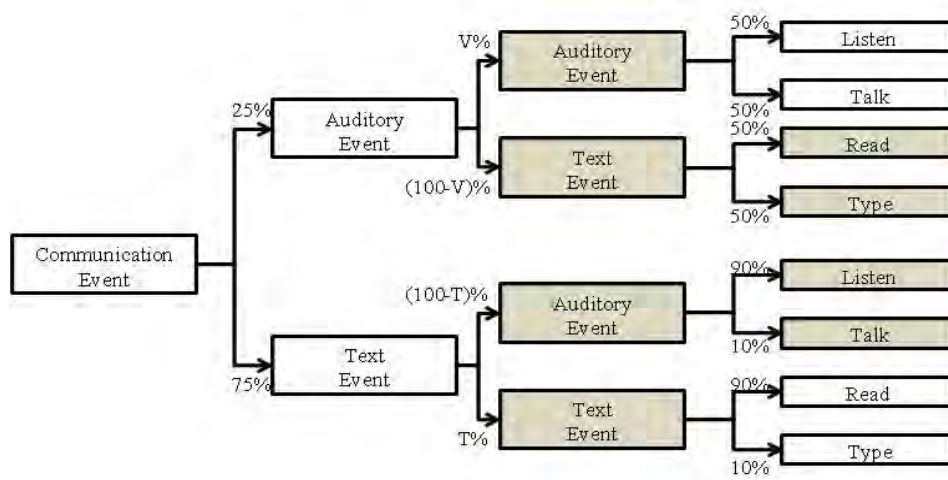
A previous model of pilot mental workload [3] was utilized to understand the impact of communications modality. This model employed functional analysis and task

allocation to construct an executable architecture of the multiple RPA system. This architecture was then replicated within the Improved Performance Research Integration Tool (IMPRINT) to estimate the pilot's workload under various mission segments, such as handover, transit, emergency, benign and dynamic surveillance, etc. This model relied on subject matter expert input to develop distributions for the length, frequency, and difficulty of the events that induce workload on the pilot. The original research on this model indicated that workload was particularly high during what were termed dynamic mission segments. These mission segments often involve high levels of communication between the pilot and external actors to facilitate the tracking or observation of moving targets. High levels of communication resulted in particularly "high" pilot workload while operating a single aircraft and, "excessive" workload while controlling multiple dynamic-mission aircraft. The original research indicated that a reduction in pilot workload imposed by communication would be necessary to facilitate MAC.

To understand the potential impact of communication modality on operator workload, the communications portion of the earlier workload model was modified to permit communications events to be reallocated to alternate communications modalities. The revised model permits communication events that were originally allocated to the auditory channels where the operator listens and speaks to the visual and fine motor channels where the operator reads and types, or vice versa.

Figure 6 depicts the high level structure of the revised communications model. The gray boxes indicate model elements that were added to facilitate this particular evaluation. Communication events are generated with a mission segment dependent frequency and their interarrival times are exponentially distributed. In the original model,

as a communication event is generated, it is assigned as either an auditory event or a text-based event with 25% of the events being allocated as auditory events and the remaining allocated as text events. Half of the auditory events then required the pilot to talk or listen while 90% of the text events required the pilot to read while only 10% of the events required the pilot to type a response.



**Figure 6: Modified communication model of pilot workload**

To conduct the current evaluation, the model was modified as shown above. The auditory and text events shown in *gray* have the potential (through a notional device or software) to either pass an auditory or text event as a respective auditory or text event or to convert an auditory event to a text event or convert a text event to an auditory event. With this modification, it is assumed that the characteristics of the communication are due to communication needs, such that if a text event in the original model had a 90% chance of providing an input to the pilot and only a 10% chance of an output to the pilot, a text event converted to an auditory event has a 90% probability to require the pilot to listen and only a 10% probability to require the pilot to talk. The parameters  $V$  (for Voice

reallocation) and  $T$  (for Text reallocation) provide the ability to convert auditory or text events to its compliment. If  $V$  and  $T$  are both 100%, the revised model is the same as the original model. Reducing either of these parameters permits a portion of one type of communication event to be reallocated to the complimentary communication event. Although not shown, it is then assumed that some percentage of the final events generate a repeat communication event, indicative of a continued conversation. This aspect of the model was not changed.

### ***Experimental Design***

For this paper, a total of six “levels” of voice/text allocation were selected such that the percent of voice communication were varied between 0 and 100 percent. For levels of voice communications less than 25%,  $V$  was varied while  $T$  was maintained at 100%. However, for levels of voice communications greater than 25%,  $V$  was maintained at 100% while  $T$  was varied to achieve the desired communications levels. All analysis was performed for a 10 hour dynamic mission segment with a single pilot operating the aircraft. Although IMPRINT does not currently have built-in Monte Carlo functionality for the metrics of our concern, an external batch application was developed to automate replications. A total of 10 replications for each of six levels using 10 different random number seeds were performed to gather the output data.

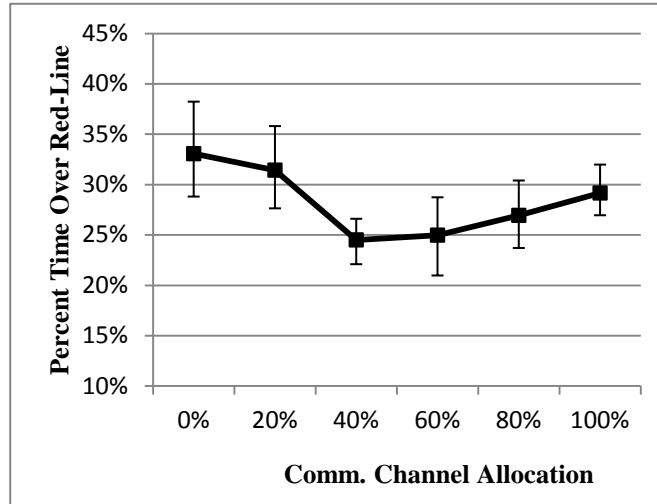
The output of the IMPRINT model was analyzed to determine the proportion of time that the operator would experience workload values over a specified task saturation threshold. A workload value of 60 was calibrated to be about the 90% of operator “red-line”, which indicates the workload value a pilot can experience without degraded

performance [10]. The mean and variance across the 10 replications for each communication ratio was calculated. Analysis of Variance (ANOVA) and the Tukey post-hoc tests were employed determine the statistical differences between the average of percent time over threshold.

## **Results**

Figure 7 shows the percent time over threshold as a function of the percentage of voice communication. A one way ANOVA indicated a significant effect of the percent of voice communication upon the percentage of time over threshold ( $p < 0.001$ ). As shown in Figure 6, the percent of time over threshold is reduced as the percent of voice communication is increased from 0% to 40%. At 40% voice communication the percent time over threshold is reduced to 24.5% compared to 33.1% with 0% voice communication. This change is statistically significant. The change in percent time over threshold is statistically insignificant as the percent of voice communication is increased from 40% to 60%. This trend indicates that pilot workload is reduced by the use of both auditory and text-based communications in this system.





**Figure 7: Percent Time Over Threshold as the percentage of reallocated voice events**

Results further show that the percent time over threshold is greater at 0% voice than at 100% voice communications. This might have been expected as reading and typing likely conflicted directly with other tasks being performed by the pilot, including visually monitoring the status and manipulating the controls of the RPAs. As such workload is highest when all of the communication is allocated entirely to the visual channel.

## **Conclusions**

The model indicates that by deliberately allocating communication between auditory and text-based modalities the pilot's workload and particularly the percentage of time the pilot operates beyond their task saturation red-line can be statistically reduced. The model shows that the percent of time over red-line is greatest when all of the communication is allocated to the text-based communications such that zero percent of

the communication is allocated to voice. This type of communication is most likely to conflict with other tasks involving the visual system to monitor the RPA and the small motor system, which is used by the pilot to control the RPA. As communication events are moved from text to auditory, the workload decreases. However, as more communication is moved to the auditory channel, the percent of mission time over the red-line to increases. The increase likely occurs as the auditory tasks begin to overlap and conflict with one another to increase workload. There appears to be an optimal allocation of communications between voice and text modalities to achieve the lowest workload given a constant traffic load. Future research will examine dynamic reallocation of modalities.

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