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Unmanned Tactical Autonomous Control and Collaboration (UTACC) human-machine integration measures of performance and measures of effectiveness

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MONTEREY, CALIFORNIA

THESIS

UNMANNED TACTICAL AUTONOMOUS CONTROL AND COLLABORATION (UTACC) HUMAN-MACHINE INTEGRATION MEASURES OF PERFORMANCE AND MEASURES OF EFFECTIVENESS

by

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June 2017

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The Marine Corps Warfighting Lab's Unmanned Tactical Autonomous Control and Collaboration (UTACC) program seeks to integrate Marines and autonomous machines to address the challenges encountered in the complex battlefield environment of the twenty-first century. In order to harness its combat capabilities, the Marine-machine team must be able to communicate. Successful integration of the Marine-machine team relies on choosing the right interfaces to achieve man-machine communication, whether they are audio, visual, haptic, electromagnetic, or some method yet discovered.

This thesis seeks to help determine the correct sensor suite needed to address the information exchange requirements for a successful Marine-machine team. The authors conducted their research using a top-down approach that started at the doctrinal level and finished with the Marine Corps Tasks List. The result is a recommended table of measures of effectiveness (MOEs) and measures of performance (MOPs) for insertion into the Marine Corps Task List to evaluate the communication nodes utilized by the Marine-machine team. Future research should seek to develop additional MOEs/MOPs deemed necessary for the progress of UTACC.

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UNMANNED TACTICAL AUTONOMOUS CONTROL AND COLLABORATION (UTACC) HUMAN-MACHINE INTEGRATION MEASURES OF PERFORMANCE AND MEASURES OF EFFECTIVENESS

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LIST OF ACRONYMS AND ABBREVIATIONS

AoA	analysis of alternatives
AC	air carrier
C2	command and control
CJCS	Chairman of the Joint Chiefs of Staff
COE	campaign of research and experimentation
COI	critical operational issues
CONOPS	concept of operations
DAU	Defense Acquisition University
DC, CD&I	Deputy Commandant, Combat Development and Integration
DOE	design of experimentation
DOD	Department of Defense
DOT&E	Director, Operational Test and Evaluation
DT1	Developmental Test 1
EF21	Expeditionary Force 21
GC	ground carrier
GPS	Global Positioning System
HMI	human-machine interface
IA	interdependence analysis
IROC	intuitive robotic operator control
ITL	in the loop
LTA2	Limited Technical Assessment 2
MCDP	Marine Corps Doctrinal Publication
MCRP	Marine Corps Reference Publication
MCT	Marine Corps Task
MCTL	Marine Corps Task List
MCWL	Marine Corps Warfighting Laboratory
MCWP	Marine Corps Warfighting Publication
MEF	Marine Expeditionary Force
MET	Mission Essential Task
METL	Mission Essential Task List

MOE	measure of effectiveness
MOP	measure of performance
MTS	modular tactical system
NATO	North Atlantic Treaty Organization
NPS	Naval Postgraduate School
OPD	observability, predictability, and directability
OTL	on-the-loop
SOW	statement of work
SoS	system of systems
TTPs	tactics, techniques, and procedures
UAV	unmanned aerial vehicle
UCD	User Centered System Design
UGV	unmanned ground vehicle
UIS	user interface system
USMC	United States Marine Corps
UTACC	Unmanned Tactical Control and Collaboration

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I. INTRODUCTION

This is a follow-on thesis to the Kirkpatrick and Rushing (2016) thesis regarding development of MOEs and MOPs for the Unmanned Tactical Autonomous Control and Collaboration (UTACC) program. UTACC is currently a complex robotic program, and the authors focused on the system-agnostic capabilities that are required for effective communication between Marines and machines. As Kirkpatrick and Rushing (2016) state, "It is a concept that has the potential to change the relationship of man and machine on the battlefield forever. The concept employs a team of aerial and ground robots, in conjunction with complex software enabling their interaction and sensor information exchange, to work as semi-autonomous teammates with a small Marine Corps unit" (Kirkpatrick & Rushing, 2016, p. 1).

Just as in the Kirkpatrick and Rushing (2016) thesis, the authors focused on previous UTACC theses to serve as the foundation and starting point into researching autonomy and robotics in war through the lens of the man-machine team. According to Chen and Barnes (2014) and reiterated by Kirkpatrick and Rushing (2016), the two main types of interaction between man and machine can be classified as either "on the loop" (OTL) or "in the loop" (ITL). OTL interaction is the preferred method of interaction because it meets the UTACC requirement of decreasing the cognitive load on the human. Kirkpatrick and Rushing (2016) created quantifiable metrics to determine how well UTACC supports "on the loop" interaction. The authors took this research and applied it to the man-machine communication problem set.

Following in Kirkpatrick and Rushing's (2016) MOE and MOP work, this thesis recommends MOEs and MOPs to evaluate the communications modalities required to support man-machine teaming in a way that supports "man on the loop" interaction. This will support the process towards maturing UTACC for eventual use by the warfighter.

A. VISION OF UTACC

As the UTACC program matures, the Marine Corps Warfighting Laboratory integrates the program into its campaign of experimentation (COE). MCWL has used testing ranging from limited technical assessments to developmental testing to evaluate new functionality in the program. In addition to directly testing, MCWL also sponsors events for academia and industry to participate and drive innovation. Each of these events generates new data sets that can be used to further the UTACC program and assess its likelihood of long-term success, justify funding, and continue research projects. The UTACC end state is incorporation into a program of record throughout the USMC.

The ability of the Marine Corps to not only wage war but also conduct many other missions will drastically change with the integration of UTACC as an autonomous member of the fire team. A key benefit to integrating an autonomous robot is their ability to do the "dull, dangerous and dirty" (Singer, 2009, p. 63) jobs that are currently conducted by humans. Not only could these jobs be performed by robots, but working in a collaborative environment with robots would allow humans to leverage the machine's capabilities that exceed the limits associated with a single human. Moreover, a single human could operate numerous robots thereby using the robots as a swarm and removing humans from the most dangerous portions of the battlefield (Jameson, Franke, Szczerba, & Stockdale, 2005, p. 2).

B. NECESSITY OF MOP/MOE

When research focus is lost and the warfighter's input is minimized, programs tend to morph into something that is "pretty" or "gold plated" instead of a program that is useful. To ensure the success of any developmental program, accurate, well defined MOEs and MOPs are crucial. The creation of MOEs and MOPs helps keep programs on track throughout their development. Designed specifically for this purpose, "The assessment process uses MOPs to evaluate task performance and MOEs to determine progress of operations toward achieving objectives and ultimately the end state" (U.S. Joint Chiefs of Staff [USJCS] J-7, 2011, p. ix).

C. THESIS IMPACT AND ORGANIZATION

The authors focused their research on a very specific piece of the UTACC program: human-machine interface (HMI) MOEs and MOPs. Narrow in its scope, this thesis focuses on the ability for Marine-machine interaction to take place, a crucial and necessary problem that requires resolution for UTACC to succeed. Developing MOEs and MOPs to evaluate the various sensors and communication interfaces is one of the first steps in selecting the right technology. Once solved, these HMI MOEs and MOPs will lay the framework for the development of additional UTACC MOEs and MOPs as the program evolves.

This thesis consists of five chapters. Chapter I introduces the thesis and the purpose behind the research efforts, including the Marine Corps Warfighting Lab's vision for the UTACC program and the impact this research will have on the Marine writ larger. Chapter II, the literature review, explores several fundamental publications and documents as they pertain to developing UTACC MOEs and MOPs. Those publications and documents include United States Marine Corps Missions, Doctrine and tactics, techniques, and procedures (TTPs), Marine/Machine Integration, the principle of observability, predictability, and directability (OPD) as it pertains to autonomous systems, current communication interfaces and finally the HMI MOPs and MOEs as they relate to the military technology selection process.

Chapter III, Research Methodology and Related Factors, details the HMI MOPs and MOEs selection process. After an overview of the basic systems engineering process, the authors present UTACC definitions, assumptions, constraints, and the role USMC doctrine and TTPs play into the MOE and MOP process. Finally, the layers of analytical development are described, laying the framework for the construction of the HMI MOE and MOPs.

Chapter IV, UTACC HMI MOPs and MOEs, is the heart of the thesis. In this chapter, the research is separated by components that are presented in a top-down approach. The recommended modifications to the MCTL organization are addressed, followed by the MOPs and finally the MOEs. Lastly, this thesis recommends future testing scenario metrics and environments for MCWL to use in order to validate our research as well as further leverage the results as the UTACC program continues to evolve.

Chapter V is a summary of our results with recommended future research. As is the case with previous UTACC theses, the HMI MOE/MOP thesis serves as another link in the chain in the evolution of UTACC and, therefore, includes recommendations meant to further the HMI components of the system.

D. CHAPTER CONCLUSION

UTACC is not simply employing robots on the battlefield; it is employing robots to revolutionize warfighting. Whereas previous theses discussed the vision, concept of operations, and overall MOEs and MOPs for the program, this thesis specifically targets the MOEs and MOPs required which ensure that the man and machine can communicate effectively to complete the mission.

II. LITERATURE REVIEW

This is the eighth thesis supporting the development of UTACC conducted through the Naval Postgraduate School (NPS). Previous theses discussed collaborative autonomy, robotics, human-machine interaction, MOEs and MOPs and USMC doctrine. Because the previous theses conducted such in depth reviews, this thesis will cover MOEs and MOPs specific to the human-machine interface while citing previous works as references. This literature review serves to summarize existing publications, current work, and thought processes relevant to UTACC design, including autonomy, doctrine, communication modalities, MOEs/MOPs, and man-machine integration.

A. USMC MISSIONS, DOCTRINE AND TTPS

For UTACC systems to be successful, they must effectively integrate into and improve the capabilities of a Marine unit's ability to accomplish its respective mission. However, there are no Marine Corps Doctrinal Publications (MCDPs) which explain how to integrate UTACC systems into the force.

MCDP 1 states that "a significant advantage can be gained by being first to exploit a development in the art and science of war" (USMC, 2011, p. 17). As mentioned in Rice, Chhabra, & Keim (2015) and paraphrased by Kirkpatrick and Rushing (2016), Expeditionary Force 21 (EF21) is the USMC's vision document how the Marine Corps of the 21^{st} century should operate. EF21 states that the modern force will "preserve the quantitative edge over opponents" and exploit "innovative concepts and approaches" (USMC, 2014). Moreover, EF21 also states that the Marine Corps of the 21^{st} Century will be "light enough for rapid response" which is supported through Jameson, et al.'s (2005) research as interpreted by the UTACC program (USMC, 2014, p. 7). Most recently, the Marine Corps released the Marine Corps Operating Concept, which explicitly drives the Marine Corps to exploit automation and "integrate robotic autonomous systems with manned platforms and Marines" (United States Marine Corps, 2016, p. 16). UTACC is exactly the program that can bridge the current gap in automation and integration.

Rice et al. state, “A mature UTACC system requires full integration of warfighting functions (intelligence, maneuver, fires, logistics, force protection, command and control)” (Rice et al., 2015, p. 17). Kirkpatrick and Rushing (2016) developed MOEs and MOPs for the UTACC system writ large, however for the Human/System Integration to be effective, it is vital to develop additional MOEs and MOPs specific to the communication between Marines and the autonomous systems. This thesis, paired with Kirkpatrick and Rushing’s work, will aid in the creation of new doctrine inclusive of the autonomous systems in line with both EF21 and the Operating Concept.

B. MARINE-MACHINE INTEGRATION

Prior research teams conducted in-depth reviews of Marine-machine integration and requirements for successful systems. Of significance to our focus on communication interfaces, Kirkpatrick and Rushing state:

> The UTACC system will need to facilitate dynamic information exchange. Gold (2009) describes the nature of complex information exchange in the four areas of “robot to human, environment to robot, human to robot, robot to environment” (Gold, 2009). In addition to these, UTACC planning would necessitate the inclusion of robot-to-robot information exchange, as the design incorporates more complex and multiple robotic systems. Sensors and computers organic to the robot systems will allow them to interact with the environment around them, but the UTACC collaborative concept will require these robots communicating this sensor data to the other UTACC elements involved in the mission including both human and machine teammate elements. It will therefore be necessary to ensure this communication piece is designed to present the sensor data to the decision maker in an effectively and timely manner. This subsequently facilitates his mental picture of the real environment around him and informs decision-making (Shattuck & Lewis Miller, 2006, p. 3). (Kirkpatrick & Rushing, 2016, pp. 9–10)

The Army Research Lab in Maryland describes the challenges of communicating with and integrating autonomous systems:

> A critical challenge of the mid-21st century will involve successfully managing and integrating the collections, teams, and swarms of robots that would act independently or collaboratively as they undertook a variety of missions including the management and protection of communications and information networks and the provision of decision-quality information to humans. Success in this aspect of command and control would depend

> upon developing new C2 concepts and approaches, in particular, developing and fielding an effective hybrid cognitive architecture that leverages the strengths of artificial intelligence and human intelligence to go along with the development of new robotic, communications, information, and systems technologies. From the various observations of workshop participants, the traditional balance between offense and defense may shift as it becomes more difficult for the defense to keep up. (Kott et al., 2015, p. 23)

To help alleviate the challenges of communicating with and integrating autonomous systems, Donald Norman and Stephen Draper presented the User Centered System Design (UCD) concept as depicted in Figure 1. Through their design process, the user remains the central focus at each stage of development by asking questions such as, "What are the goals and desires of the user, what tools do they need, what type of task are they required to accomplish, and what methods do they prefer?" (Norman & Draper, 1986, p. 2). With these questions in mind, the UCD process lays out four steps: specify the context of use; specify the requirements; create design solutions; and evaluate the designs (U.S. Department of Health and Human Services, 2015). This framework enables the designer to ensure the system being developed remains focused on the needs of the user within the context of its operating environment.

Figure 1. Four-Step UCD Process. Source: U.S. Department of Health and Human Services (2015).

The Department of Defense (DOD) published a report titled *The Role of Autonomy in DOD Systems* in 2012 that discussed the capabilities of integrating the autonomous systems in order to reduce cognitive load on the operator while simultaneously maximizing strengths of the machines:

> With proper design of bounded autonomous capabilities, unmanned systems can also reduce the high cognitive load currently placed on operators/supervisors. Moreover, increased autonomy can enable humans to delegate those tasks that are more effectively done by computer, including synchronizing activities between multiple unmanned systems, software agents and warfighters—thus freeing humans to focus on more complex decision making. (DOD, 2012, p. 1)

Each of these reports, when combined and viewed through the lens of the Rice et al.'s definition of "collaborative autonomy," describe the challenges to humans' operating systems and the need for specific MOEs and MOPs relating to the Marine-machine integration to help shape doctrine.

C. OBSERVABILITY, PREDICTABILITY, DIRECTABILITY

The following quote from Johnson's (2014) work clarifies what it means to be observable, predictable and directable:

> Observability means making pertinent aspects of one's status and knowledge of the team, task and environment observable to others. Observability also involves the ability to observe and interpret pertinent signals. It plays a role in many teamwork patterns e.g., monitoring progress and providing backup behavior.
>
> Predictability means one's actions should be predictable enough that others can reasonably rely on them when considering their own actions. Predictability also involves considering other's actions when developing one's own. It is essential to many teamwork patterns such as synchronizing actions and achieving efficiency in team performance.
>
> Directability means one's ability to direct the behavior of others and complementarily by directed by others. It includes explicit commands such as task allocation and role assignment as well as subtler influences, such as providing guidance or suggestions or even providing salient information that is anticipated to alter behavior, such as a warning. Teamwork patterns that involve directability include such things as requesting assistance and querying for input during decision making.
>
> By using the OPD framework as a guide, a designer can identify the requirements for teamwork based on which interdependence relationships the designer chooses to support. The framework can help a designer answer questions such as 'What information needs to be shared,' 'Who needs to share with whom,' and 'When is it relevant.' The goal of the designer is to attain *sufficient* OPD to support the necessary interdependent relationships. (Johnson, 2014, pp. 68–70)

This OPD framework shifts the focus from one individual component, either the robot or the human, to the team components and how they both affect one another (Johnson, 2014). Traum, Rickel, Gratch, and Marsella (2003) use three categories to discuss the relationship between machines and humans: agents in supporting individual team members, agents supporting the team as a whole, and agents as an equal team member (Traum et al., 2003). The UTACC program falls in the third category of assuming an equal role as the other team members. As noted by the National Research Council:

> This is the hardest role for a software agent to assume, since it is difficult to create a software agent that is as effective as a human at both task performance and teamwork skills. Instead of merely assisting human team members, the software agents can assume equal roles in the team, sometimes replacing missing human team members. It can be challenging to develop software agents of comparable competency with human performers unless the task is relatively simple. (National Research Council, 2014, p. 53)

Through answering the framework's questions, the Marine Corps will be more able to adapt future doctrine to integrate the effectiveness and performance of the communication and interaction between the system and human.

D. COMMUNICATION INTERFACES

In viewing the UTACC problem set, redundant communication interfaces are essential to achieve mission accomplishment in the wide-ranging tactical environment. Marines currently use three sensory modes in order to communicate amongst themselves at the fire team level: visual, audio, and haptic. By adding a machine to the fire team, electromagnetic communication also becomes a viable interface. The selection of the correct mode or modes of communication directly relies on the environment in which the team is operating. When noise discipline is required, audio communication is a last resort, but visual, haptic, and electromagnetic are all viable modes. Conversely, when noise discipline is no longer a constraint, audio communication may be the most efficient way to disseminate orders and directions to team members. The remainder of this section will provide an overview of the available interfaces and is discussed in greater depth in later chapters.

Visual communication is the primary method by which fire teams communicate. Additionally, the work of Calinon, Evrard, Gribovskaya, Billard, and Kheddar shows that robots, through observation of human behavior, can learn collaborative manipulation tasks (Calinon et al., 2009). This would allow the fire team to create team specific signals as well as enable the robot to relay and replicate hand-arm signals, creating a feedback loop. Some of the limitations of visual communications are poor visibility, restricted terrain, replication error when relaying through the team, as well as enemy interception (United States Army, 1987, p. 1-1).

Audio communication is easy to understand, straightforward, and is situationally adaptive. While generally used in situations that do not require noise discipline, a loud battlefield environment may reduce the effectiveness of this modality (United States Marine Corps, 2002, pp. 3-35). Voice recognition software coupled with a hands-free radio, like the Safariland Group's Tactical Throat Microphone Headset as shown in Figure 2, is an example of achieving the audio interface. While voice recognition software is not ideal for everyday use such as typing emails or sending text messages, limiting the number of commands and the manner in which the commands are stated allows for customized software, tailored to the man-machine teaming requirements. Moreover, the Marine Corps uses the NATO phonetic alphabet to enable more accurate audio recognition in radio communications; this type of simplification can also improve man-machine communication.

Figure 2. Safariland Group’s Tactical Throat Microphone Headset. Source: Safariland Group (n.d.).

Haptic communication is the least commonly used method of communication in pure human-human interaction because it relies on the sense of touch. However, by introducing a machine to the fire team, this method becomes a more viable option by using devices such as Schätzle et al.’s ergonomic vibrotactile feedback apparatus, shown in Figure 3. This device overcomes the limitations of the audio and visual interfaces as well as provide machine acknowledgement of receiving various human commands (Schätzle et al., 2010, p. 675).

Figure 3. Ergonomic Vibrotactile Feedback Device. Source: Schätzle et al. (2010).

With the addition of a machine into the fire team, electromagnetic communication, such as personal digital assistant, iPad, smart glasses, or modular system as shown in Figure 4, becomes a fourth interface option for communication. According to Fong et al., this type of interface is gaining in popularity due to reduced weight, portability, and touch-sensitive displays (Fong et al., 2001, p. 301). As early as 2000, Perzanowski, Adams, Schultz, and Marsh showed the validity of using electromagnetic devices “as a part of a multi-modal interface for interacting with an autonomous robot” (Perzanowski et al., 2000, p. 1).

Figure 4. Black Diamond Advanced Technology's Modular Tactical System (MTS). Source: Soldier Systems (n.d.).

Because several information exchange technologies are in their infancy, the effort to identify and codify the MOEs and MOPs is a vital task to ensure the final product satisfies the real-world requirements.

E. MOEs AND MOPs

As the UTACC program matures, well measured MOEs and MOPs will be paramount to the selection process communication and integration of the Marine-machine team. This thesis will focus directly on outlining MOEs and MOPs for achieving HMI through reliable and redundant communication.

Linking the results of tactical actions to the overall mission objectives, the Joint Chiefs of Staff J-7 defines the concept of Assessment using two metrics: MOPs and MOEs (USJCS J-7, 2011, p. viii). MOPs "evaluate task performance" or "task accomplishment" (USJCS J-7, 2011, p. ix). They are typically "developed and assessed at the component level for military tasks or at the agency or organizational level for non-military tasks" (USJCS J-7, 2011, p. III-7). Because the UTACC program is still in the research and development phase, the MOP development falls under the non-military task category and is the responsibility of MCWL, in coordination with the NPS.

MOEs are the "criterion used to assess changes in system behavior, capability, or operational environment that is tied to measuring the attainment of an end state, achievement of an objective, or creation of an effect" (USJCS, 2017, p. GL-13). They provide an "accurate baseline model" for determining whether the organization's actions are achieving desired effects (USJCS J-7, 2011, p. III-9). Once the MOEs are established, the sensor(s) used to achieve HMI should be evaluated against the model proposed in this thesis.

F. CHAPTER CONCLUSION

This literature review summarized timely and relevant information primarily focused with the ability of man and machine to communicate and the most effective ways to measure the communication's performance and effectiveness. The UTACC program is a multifaceted problem set attempting to harness the potential of the man-machine team.

While this is a new and exciting field, it does not come without its challenges. As Johnson states, the solutions to this challenging problem set are viewed through the OPD framework (Johnson, 2014). However, current doctrine does not include necessary MOEs and MOPs for the man-machine concept. Additionally, understanding and developing the relationship of and the communication between man and machine is a difficult issue that this thesis will seek to address. This thesis will capitalize on the aforementioned work to determine the most effective metrics for measuring communication and integration of Marines and autonomous systems.

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III. RESEARCH METHODOLOGY AND RELATED FACTORS

This chapter outlines the authors' methodology used by the authors in building appropriate HMI MOEs and MOPs. First, the basic systems engineering process is reviewed, followed by explanations of UTACC terms and assumptions relevant to the authors' research. Next, the derivation of MOE/MOPs is explained, beginning with an overview of high-level doctrine and reducing down to the detailed tasks Marines train for as outlined in the Marine Corps Task List. Finally, OPD requirements are reviewed for their applicability to the relevant MOE/MOPs, based on the uniqueness of the machine teammate.

A. BASIC SYSTEMS ENGINEERING PROCESS

As originally stated by the program sponsors and pioneered by Kirkpatrick and Rushing (2016), development of the MOPs and MOEs for this thesis and the UTACC program used the basic systems engineering processes, as shown in Figure 5, and the UTACC concept of operations (CONOPS) thesis (Kirkpatrick & Rushing, 2016). Rice et al. originally conducted an analysis of the basic systems engineering processes as defined in the Systems Engineering Management textbook (Blanchard, 2008) which Kirkpatrick and Rushing also referenced (Kirkpatrick & Rushing, 2016). Since that time, Blanchard published the 5th edition to the textbook and the authors verified that the systems engineering process referenced in previous theses remains the same (Blanchard, 2016). Based on Rice et al.'s (2015) recommendations and previous work conducted by Kirkpatrick and Rushing (2016), the authors viewed "UTACC as a system of systems (SoS) capable of independent operations while operating within the Marine Corps' command and control model to ensure unity of effort when conducting operations" (Kirkpatrick & Rushing, 2016, p. 15). According to their findings, "The steps that were most applicable to this thesis were: definition of problem, operational requirements, and functional analysis. The entire process also incorporated feedback mechanisms as an important element of concept generation" (Rice et al., 2015, p. 21). The authors focused their research on these three steps to effectively determine quantifiable metrics for the man-machine interface as specifically viewed through the lens of ensuring that humans and machines could communicate effectively over multiple modalities.

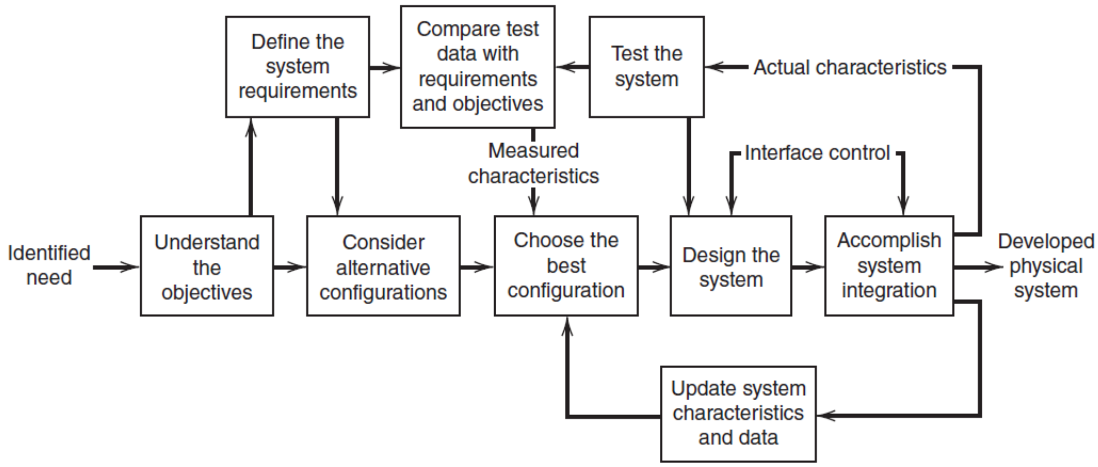

Figure 5. Systems Engineering Model. Source: Blanchard & Blyler (2016).

Kirkpatrick and Rushing (2016) used the operational requirements identified by the UTACC CONOPS thesis to drive the development of system-level MOPs and MOEs (Kirkpatrick & Rushing, 2016). Those measures were based on Performance and Related Operational Parameters, Utilization Requirements, and Effectiveness Requirements (Kirkpatrick & Rushing, 2016). As stated by Rice, et al. (2015) and paraphrased by Kirkpatrick and Rushing (2016), the conduct of the Functional Analysis served as the "heart of the concept generation" for the UTACC CONOPS thesis (Rice et al., 2015, p. 23). Kirkpatrick and Rushing (2016) used the results to develop pertinent MOPs and MOEs. The authors used the same systems engineering process to develop MOPs and MOEs for the man-machine interface resulting in key metrics for future testing and implementation. Follow on chapters discuss this research and the results in detail.

B. UTACC TERMS AND DEFINITIONS

Due to the growing number of theses in the UTACC program and the inherent requirement for consistency in terms, these definitions are directly sourced from Rice et al.'s work.

Small tactical unit–a Marine Corps infantry fire team, infantry squad, or reconnaissance team.

UTACC–armed Marine(s) conducting operations with the assistance of a mix of semi-autonomous unmanned ground and air vehicles. One UTACC system is a triad of a human component, an air component, and a ground component. (SOW, 2016)

Human Component– envisioned as a small tactical unit leader. UTACC should also be able to work with, provide input to, and receive direction from all members of a small tactical unit.

User Interface System (UIS)–a combination of devices that stimulate multiple senses in the human. For example, this might allow him to do the following: see a map of the operations area or a live video of a specific person of interest; hear a warning informing him that a component has experienced a critical system failure; or, feel a warning of nearby enemy force. In addition to providing input to the human, the UIS will also receive input from the human and then relay that input to all the other UTACC components. The human inputs can also come in a variety of ways: hand and arm signals directing the tactical movement of UTACC; verbal messages given to human teammates as well as UTACC components; touch gestures/drawings on a UTACC generated map or preformatted report.

Air Carrier (AC)–an unmanned ground vehicle capable of carrying, launching, recovering, and refueling multiple unmanned air vehicles (UAVs). In addition, the AC will be capable of carrying additional supplies (e.g., ammunition, food) for the small tactical unit as well as acting as a communications relay for the UTACC components. In the future, this vehicle will be capable of high-speed travel over rough terrain and off-road areas.

Unmanned Air Vehicle (UAV)–an aerial platform capable of carrying any number of sensors to support mission specific intelligence, surveillance, and reconnaissance (ISR) requirements and capable of vertical takeoff and landing. The UAV will be capable of serving as a vital communications relay node between geographically separated ground components.

Ground Carrier (GC)–an unmanned ground vehicle capable of carrying, deploying, and recovering multiple unmanned ground vehicles (UGVs). In addition, the GC will be capable of carrying additional supplies (e.g., ammunition, food) for the small tactical unit as well as acting as a communications relay for the UTACC components. This vehicle will be capable of high-speed travel over rough terrain and off-road areas.

> *Unmanned Ground Vehicle (UGV)*–mission specific unmanned systems capable of performing discrete ISR missions. The UGVs, similar to the UAVs, could have a variety of sensors to support mission specific ISR requirements.
>
> *Cue*–is a notification issued by the UIS to the Human Component where human intervention is not required.
>
> *Alert*–is a prompt issued by the UIS to the Human Component requiring human intervention. (Rice et al., 2015, pp. 26–27)

These terms remain relevant in the discussion of MOP/MOEs since they relate to the components of the UTACC system.

C. UTACC ASSUMPTIONS

Due to the lack of current doctrine and research in the field of man-machine teaming, the initial UTACC CONOPS included assumptions that were necessary to frame the problem; these assumptions are carried forward from thesis to thesis and modified as required. Although originally assumed that UTACC is a *technology agnostic* concept by Rice et al., subsequent analysis of alternatives (AoA) conducted by Roth and Buckler (2016) narrowed the systems and technology best suited for current UTACC developmental testing (Rice et al., 2015, p. 27). However, the incorporation of newly developed or even theoretical technologies, such as magnetic field communication, remains vital to the UTACC program. Just as Kirkpatrick and Rushing developed system specific MOPs and MOEs through a technologically agnostic methodology, the authors worked to do the same for the man-machine communication interface (Kirkpatrick & Rushing, 2016).

A key assumption made by Kirkpatrick and Rushing (2016), which the authors carried forward into this thesis, is that UTACC could apply current USMC Task List elements to verify the same results in tasks independent of whether they were performed by a human or a robot (Kirkpatrick & Rushing, 2016). Thus, the authors assume the results of the actions taken during information exchange between the man and machine team will be commensurate with the results of information exchange between an all human fire team, although the modalities or interfaces may be different.

Another assumption made by Kirkpatrick and Rushing (2016) and still valid for this thesis is that the MCTL metrics currently used in the UTACC developmental testing would "accurately reflect metrics applied to UTACC in future testing" (Kirkpatrick & Rushing, 2016, p. 18). Manpower, budget, and shifting priorities from the program sponsor may change the nature of future UTACC developmental tests; however, those changes should not affect the desired end state of the UTACC program.

D. UTACC CONSTRAINTS

The proprietary and closed nature of the Intuitive Robotic Operator Control (IROC) event held in October 2016 was a significant constraint in developing the metrics for man-machine communication was. In order to achieve a higher level of participation from industry leaders, MCWL did not allow outside researchers to attend. Although the benefit of this decision is a more open forum for participants of the event, academic research in man-machine teaming suffered.

Due to the limited nature of developmental testing, the number of tasks to be evaluated will be constrained. As a result, the proposed MOEs and MOPs which can be evaluated are also constrained. Although the above assumptions state that MCTL metrics will be used in the testing, it is currently unknown when testing will be able to accurately and effectively test the UTACC system fully, so MOEs and MOPs must be designed in a modular and adaptable way as the system evolves.

E. ROLE OF DOCTRINE AND TTPS

As originally discussed by Kirkpatrick and Rushing (2016), Marine Corps doctrine establishes the fundamentals for operations in both training and combat environments through the publication of 11 Marine Corps Doctrinal Publications (MCDP). "MCDPs are higher order doctrinal publications that contain the fundamental and enduring beliefs of warfighting" (Global Security, n.d.). In addition to the MCDPs, Marine Corps Warfighting Publications (MCWP) "have a narrower focus that details tactics, techniques and procedures (TTPs) used in the prosecution of war or other assigned tasks" and Marine Corps Reference Publications (MCRP) "contain general reference material that is more specific/detailed than the MCWPs" (Global Security, n.d.).

The Marine Corps Task List (MCTL) is a fourth element of Marine Corps doctrine which, "allows for quantifiable measurement of proficiency in military skills and capabilities" (Kirkpatrick & Rushing, 2016, p. 19). According to the MCTL Branch website:

> MCTL is the authoritative, standardized, and doctrinally-based lexicon of USMC capabilities defined as Marine Corps Tasks (MCTs) and used by units, installations and the supporting establishments in the development of Mission Essential Tasks and Task Lists (METs/METLs). METs/METLs are the list of "essential," critical, discrete, externally-focused MCTs that directly enables the execution of the organizational mission. Capabilities, defined as "MCTs" and resident in MCTL enable Commanders to document their command warfighting operational abilities as METs/METLs, providing force sourcing planners, trainers and concept developers with single common language "tasks" articulating both Joint and USMC-specific, manpower, equipment and training requirements. (United States Marine Corps, 2016)

Each Marine Corps Task (MCT) has a collection of relevant MOPs and MOEs for timely, quantifiable feedback pertaining to the unit's ability to perform the stated task to a given standard. Table 1 is an overview of how a MCT is defined, broken down into its subcomponents, and how each subcomponent is assigned its respective metrics.

Table 1. Excerpt from MCTL 2.0. Source: United States Marine Corps (2016).

MCT 5.3.1.2 Exercise Tactical Command and Control

Tactical command and control provides purpose and direction to the varied activities of a military unit. It is the means by which the Commander recognizes what needs to be done and sees to it that appropriate actions are taken. Tasks include: to order warfare degrees of readiness; to direct asset assignment, movement, and employment; and, to control tactical assets, including allied and joint forces assigned. **(JP 1-02, 3-0, 5-0, 5-00.2, MCDP 1-0, 6, NDP 6, NWP 3-21, 3-21.0 Rev A, 3-56.1 Rev A, 6-00.1, NTA 5.4.1.2)**

M1	Time	For units to respond to tasking.
M2	Time	Delay in response to orders.
M3	Percent	Of units responding appropriately to orders.
M4	Percent	Of mission objectives attained.

There are hundreds of MCTs breaking down every aspect of Marine Corps operations with thousands of associated MOP/MOEs. Existing MCTs do not, however, account for the evaluation of man-machine teams that may have a different set of grading criteria to assess their capabilities. Chapters IV and V discuss the criteria further.

F. ANALYSIS DEVELOPMENT LAYERS

To capture accurately the technical performance parameters while still incorporating the tactical requirements, the developmental layers of analysis must be clearly understood. These layers provide the framework in which the MOEs and MOPs are nested and are depicted in Figure 6. The Chairman of the Joint Chiefs of Staff (CJCS) J-7 serves as the 30,000-feet view for the author’s approach by articulating the joint definitions and purposes of MOEs and MOPs. Next, the Director, Operational Test and Evaluation (DOT&E) is responsible for the operational testing and evaluation of major DOD acquisition programs. They provide a more robust approach to developing metrics to accurately measure a system’s effectiveness. The final layer is the proposed UTACC MOEs and MOPs that are further refined by selected MCTs of interest and the OPD Interdependence Analysis (IA) Tables presented in Zach’s *Coactive Design* thesis (Zach, 2016).

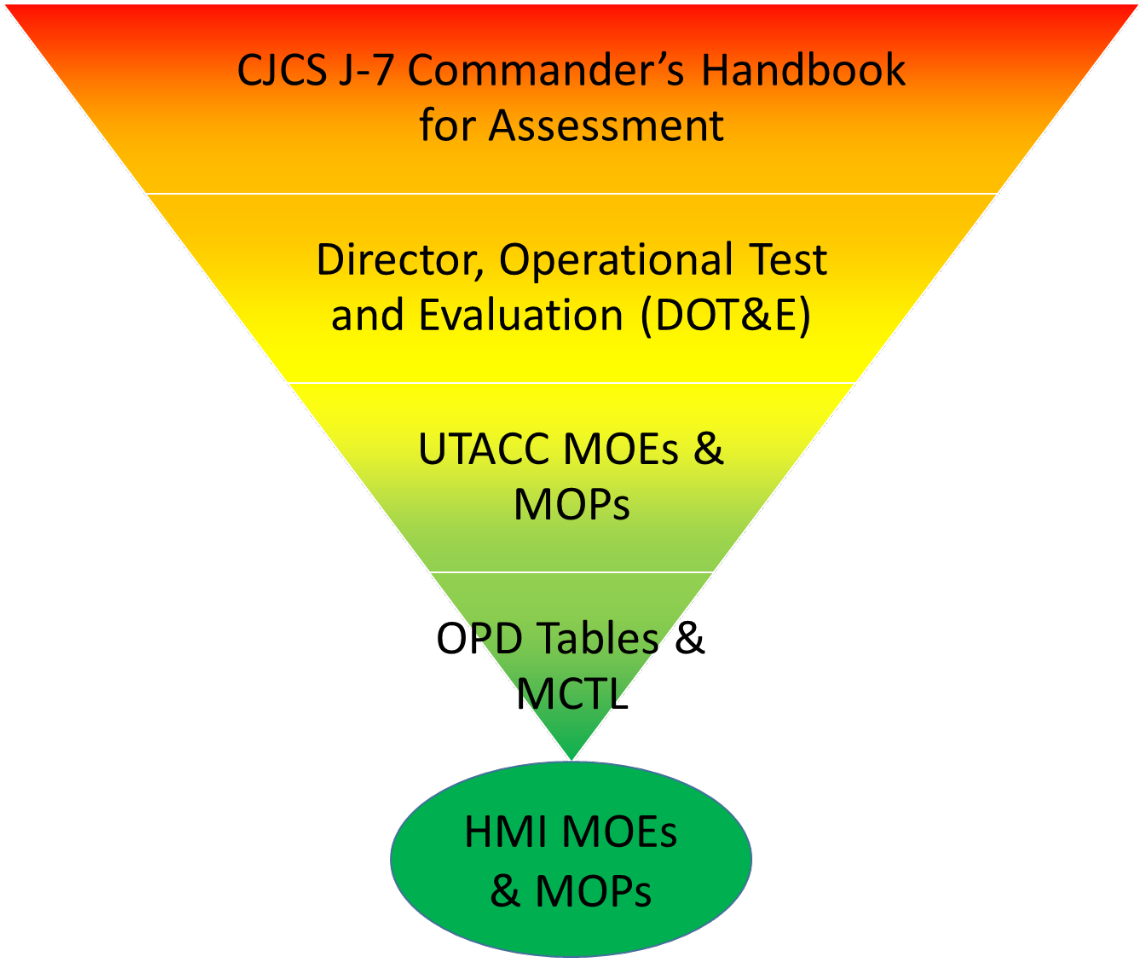

Figure 6. Framework for HMI MOE and MOP Development

1. CJCS J-7 Commander's Handbook for Assessment

The CJCS J-7's *Commander's Handbook for Assessment Planning and Execution* provides a starting point for the development of the UTACC system MOEs and MOPs. Linking the results of tactical action to overall mission objectives, MOEs and MOPs are developed metrics used to assess a system:

> The assessment process uses MOPs to evaluate task performance and MOEs to determine progress of operations toward achieving objectives, and ultimately the end state. MOEs help answer questions like: "are we doing the right things, are our actions producing the desired effects, or are alternative actions required?" MOPs are closely associated with task accomplishment. MOPs help answer questions like: "was the action taken, were the tasks completed to standard, or how much effort was involved?" … The intent in developing MOEs and their associated indicators is to build an accurate baseline model for determining whether joint and supporting agency actions are driving target systems toward or away from exhibiting the desired effects. As strategic and operational level effects are seldom attained or exhibited instantaneously, MOEs provide a framework for conducting trend analysis of system behavior or capability changes that occur over time, based on the observation of specific, discrete indicators. (USJCS J-7, 2011, pp. 11–12)

The key purpose in developing MOEs and MOPs is to drive a system toward mission success.

2. Director, Operational Test and Evaluation

DOT&E is the U.S. government's primary office responsible for the operational testing and evaluation of major DOD acquisition programs. While the UTACC program is currently in the developmental testing phase, it is important the guidelines and procedures laid out by DOT&E are taken into consideration early in the design process. As depicted in the "Vee" Developmental Model in Figure 7, developer and user perspectives are incorporated throughout the entire systems engineering process. These perspectives, when captured early in the design process, help prevent system setbacks and ensure the program continues to meet user requirements.

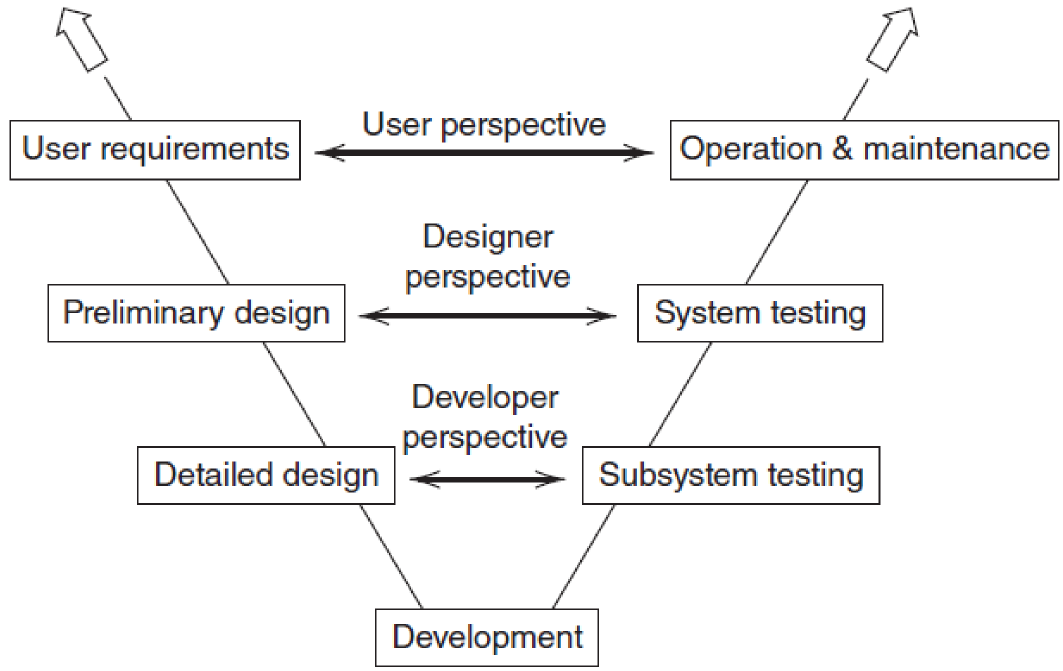

Figure 7. Generic “Vee” Developmental Model. Source: Blanchard & Blyler (2016).

Laid out in their “Mission Focused Evaluation - Guidance,” DOT&E articulates several concepts which will be used in Chapters IV and V to identify and formulate the MOEs and MOPs necessary for the success of UTACC’s Marine-machine interface solution (DOT&E, n.d., p. 1). Foremost, metrics are essential for the success of any test design effort. Selecting the right metrics requires a thorough understanding of the critical operational issues (COIs), or more plainly stated, “The key operational effectiveness or suitability issues that must be examined in operational test and evaluation to determine the system's capability to perform its mission” (DAU, n.d.).

As DOT&E highlights, “The metrics will provide a determination of mission capability, lend well to good experimental design [Design of Experimentation], and encapsulate the reasons for procuring the system” (DOT&E, n.d., p. 1). When creating metrics, DOT&E uses two types, either discrete or continuous. Continuous metrics incorporate some type of quantitative feedback into their outputs. An example output of a continuous metric is shown in Table 2. Although the “meets threshold” box is still a yes or no, the key to the metric is in the variable.

Table 2. Continuous Metric Example

Task	Variable	Meets Threshold
Relay information to fire team leader	100 meters	Y

Conversely, discrete metrics can best be described as pass/fail metrics. An example of a discrete metric is shown in Table 3.

Table 3. Discrete Metric Example

Task	Meets Threshold
Relay information to fire team leader	Y

Unlike a continuous metric that provides context for measuring effectiveness, a discrete metric discards information and is limited in its usefulness. In the discrete metric example, it is unknown whether the machine is sitting immediately beside the fire team leader or located at a much greater distance; we lose content. For the purpose of this thesis, discrete metrics are used to formulate MOEs. Furthermore, to provide context, continuous metrics are nested inside the discrete metrics as MOPs. This idea is captured in Table 4.

Table 4. Discrete/Continuous Metric Application to MOEs and MOPs

MOE	Task		Threshold
1.0	Sensor is resilient to operating environment		Y
MOP	Task	Variable	Threshold
1.0.1	Sensor is waterproof	50 m	Y
1.0.2	Sensor is windproof	40 kts	Y
1.0.3	Sensor is temperature-proof	-30^{o} to 180^{o} F	Y

Lastly, DOT&E stresses that “metrics chosen must also be well-defined and meaningful. Evaluators should consider example operational scenarios to ensure that the metric can be unambiguously measured (scored) and calculated in all cases” (DOT&E, n.d., p. 2). Due to the dynamic operating environment of the Marine Corps, this principle of matching the metrics to environments will serve as a fundamental building block in the following chapters.

3. UTACC MOEs and MOPs

As mentioned at the beginning of this section, when developing MOEs and MOPs, the unique incorporation of a machine into the fire team leads to supplementary considerations. In addition to the traditional tactical requirements, a fire team must be able to meet technical tasks which must also be included to effectively evaluate and measure machine-specific contributions.

Based on the scope of testing during MCWL’s Developmental Test 1 (DT1), the tactical requirements are limited to simple fire team concepts such as maintaining current position within the fire team and changing formations when given the proper signal. The preponderance of these tactical tasks are linked to MCTL 2.0 and provide the starting point for refining the UTACC MOEs and MOPs into HMI specific MOEs and MOPs. Table 5 depicts the preliminary UTACC MCTs of interest.

Table 5. Preliminary UTACC MCTs of Interest. Source: United States Marine Corps (2016).

MCT	Description
5	Exercise Command and Control
5.1	Acquire, Process, Communicate Information, and Maintain Status
5.1.3	Maintain Information and Force Status
5.1.3.2	Provide Positive ID of Friendly Forces Within AO
5.3	Direct, Lead, Coordinate Forces/Operations
5.3.1	Direct Operations
5.3.1.2	Exercise Tactical Command and Control

Technical tasks are much more difficult to capture, as there is no real starting point to draw from in current Marine Corps doctrine or TTPs. The authors relied on the Coactive Design IA tables (Zach, 2016) and concurrent UTACC Immediate Actions research (Chenoweth & Wilcox, 2017) to form the initial framework to begin capturing required technical parameters. As seen in Table 6, the implied tactical tasks are in the leftmost column. By breaking each task down into specific OPD requirements necessary for the success of the man-machine team, specific, technically focused MOPs are derived. These OPD requirements help narrow down the necessary technical measures for incorporation into the UTACC MOEs and MOPs.

Table 6. Coactive Design IA Tables. Source: Zach (2016).

			Option 1			Option 2			Option 3			
Tasks	Subtasks	Capacities	UAS	UGS	M	UGS	UAS	M	M	UAS	UGS	OPD requirements
Maintain COP	Send Imagery and Data Back to COP and to Leaders		Yellow	Green	Red	Yellow	Green	Red	Gray	Gray	Gray	They may be positioned during this portion of the mission to extend the communication lines, where the UxVs serve as intermediate relay nodes in the communication link between the objective back to a HHQ or adjacently operating unit that would otherwise experience degraded or no communication links.
Tactical Alerts and Cueing	Provide Alert Message to Team When Critical Tactical Events Occur (Team Response Required)	Recognize Tactical Alert Scenario	Yellow	Yellow	Red	Yellow	Yellow	Red	Gray	Gray	Gray	The UxVs should always notify the team of critical tactical events, including: when in the vicinity of checkpoints and other important grids, when a high value target or be on the look out was spotted, direction and distance of enemy contact, etc.
	Provide Cues to Team When Less Than Critical Tactical Events Occur (Team Response Optional)	Recognize Cueing Scenario	Yellow	Yellow	Red	Yellow	Yellow	Red	Gray	Gray	Gray	The Team Leader may also want the UxVs to notify him of additional events like approaching traffic, or potential hot spots along the route where possible IEDs may be emplaced, etc.

G. CHAPTER CONCLUSION

The development of MOEs and MOPs is a difficult task, which requires input and validation from multiple sources. Add in the complexities of a man-machine team and the number of issues grows exponentially. However, by using the methodology in Table 6, the authors were able to narrow their focus to the design of those specific MOEs and MOPs necessary for the successful communication between man and machine.

IV. UTACC HMI MEASURES OF EFFECTIVENESS AND MEASURES OF PERFORMANCE

A preliminary look at the MCT 5 family of tasks, “Exercising Command and Control,” served as the basis for the creation of UTACC HMI MOEs and MOPs. From the Marine Expeditionary Force (MEF) level to the fire team level, Marine Corps Command and Control is an absolute necessity in ensuring the success of Marine Corps operations. Due to the uniqueness and complexities accompanying the UTACC program, additional MOEs and MOPs were derived from insight provided by the prior research of Zach (2016), Johnson (2014), and Rice, et al. (2015) as well as the current research of Chenoweth and Wilcox (2017). While the current MCTL lacks metrics for the UTACC program, nesting newly developed sub-tasks within the current framework allows for a rapid integration with minimal disruption.

A. MOPs

As stated in Chapter II, MOPs evaluate task performance or task accomplishment (USJCS J-7, 2011, p. ix). With this in mind, the authors worked with the assumption that, as long as a metric is applied, the task’s performance can be assessed. The MOPs are not designed to state whether the mission was accomplished, but only to show how the human and machine are interacting compared to the objective standards.

As an example, a metric for audio communication from the machine to the human may be “did the human hear the machine.” If the answer is “yes,” then the metric was achieved. However, the MOP does not explain whether the machine communicated the correct information or if the human understood the correct information. It only answers the question of “did the human hear the machine.” Both a metric and a way to take the measurement are vital to succeed in effectively measuring the MOPs; if either is lacking, evaluation of the MOP may not be correct. Also critical to the MOPs and their use is the threshold that must be achieved. If, for example, the MOP measures a percentage of correct commands communicated, then that result must be compared against a threshold to determine whether it meets an acceptable value.

Table 7 depicts an excerpt from MCTL 2.0 and the MOPs associated with MCT 5.3.1.2- *Exercise Tactical Command and Control*.

Table 7. Excerpt from MCTL 2.0. Source: United States Marine Corps (2016).

M1	Time	For units to respond to tasking.
M2	Time	Delay in response to orders.
M3	Percent	Of units responding appropriately to orders.
M4	Percent	Of mission objectives attained.

B. MOEs

As stated in Chapter II, MOEs are the "criterion used to assess changes in system behavior, capability, or operational environment that is tied to measuring the attainment of an end state, achievement of an objective, or creation of an effect" (USJCS, 2017, p. GL-13). The authors of this thesis focused on the MOEs' use in assessing whether or not the objective was achieved during the testing. The MOE associated with Table 7's MOPs is MCT 5.3.1.2, *Exercise Tactical Command and Control*, or more simply, "Was tactical command and control exercised effectively?" An MOE is defined in such a way that the associated MOPs support the MOE. Therefore, if the threshold standards for the associated MOPS are met, then the MOE will be met.

C. MCTL ORGANIZATION AND WARFIGHTING

After a thorough review of MCTL 2.0, the authors focused on the addition of a MCT sub-task rather than rewriting the current MCTL due to the limited nature of robotics throughout the Operating Forces. Based on the scope of this thesis, the authors recommend that an additional sub-task be listed as 5.1.4- *Maintain Two-Way Communications with Autonomous Robotics* which would be subordinate to 5.1- *Acquire, Process, Communicate Information, and Maintain Status* and ultimately subordinate to MCT 5- *Exercise Command and Control* (United States Marine Corps, 2016). Table 8 depicts this recommended hierarchy.

Table 8. Recommended Update to MCTL 2.0. Adapted from United States Marine Corps (n.d.).

MCT	Title
5	Exercise Command and Control
5.1	Acquire, Process, Communicate Information, and Maintain Status
5.1.1	Provide and Maintain Communications
5.1.2	Manage Means of Communicating Information
5.1.3	Maintain Information and Force Status
5.1.4	Maintain Two-Way Communication with Autonomous Robotics

The recommended location of this new sub-task was chosen due to the intrinsic communication requirement of UTACC "acting collaboratively with each other and with humans" (NPS & MCWL, 2016, p. 1). The chosen interfaces for the communication between UTACC and Marines must not overburden the Marine's cognitive load while maintaining effective command and control. Table 9 depicts the sub-tasks subordinate to MCT 5.1.4 which will measure the performance over the different communication modalities as discussed in Chapter II.

Table 9. Recommended Update to MCT 5.1.4

MCT	Title
5.1.4	Maintain Two-Way Communication with Autonomous Robotics
5.1.4.1	Identification of Team Members
5.1.4.2	Explicit Human-Initiated Communication
5.1.4.3	Explicit Robot-Initiated Communication

D. TESTING ENVIRONMENT

The key to an accurate evaluation of the UTACC program through the authors' MOEs and MOPs is ensuring the correct item is evaluated at the correct time in the correct way. More simply, UTACC should not be penalized because another fire team member was not on task. The team failing in this manner would be the fault of a human fire team member, not the robot.

During UTACC's DT1, this situation manifested itself several times. DT1 was a preliminary test that focused on the UTACC software. To assist in evaluating and logging data during the test, software toolkits were utilized which, among other items of interest, displayed the global positioning system (GPS) data of the human fire team members and the robot. One of the issues encountered throughout testing was GPS error in locating both the humans and the robot. GPS data was continually transmitted to the UTACC software, which then computed a velocity vector. The robot used the velocity vector to maintain its position or move into the correct position. When inaccurate GPS data was directed to UTACC, an invalid velocity vector was sent to the robot. Consequently, UTACC's algorithms would maneuver the robot out of position. At a surface level, one could argue that the software's algorithms failed in that they did not compute velocity vectors that accurately positioned the robot due to poor filtering of the data. However, after closer examination of the testing toolkits, the UTACC algorithms were accurately computing velocity vectors based off the GPS data received. In other words, the UTACC software was correctly doing what it was supposed to do while something outside the testing—the navigation data—was failing.

With this example in mind, future testing of UTACC HMIs must ensure the testing environment creates a scenario that accurately captures the right data points for the MOPs under test. With four different modes of possible man-machine communication, isolating and independently testing each mode is critical in evaluating the UTACC HMI system as a whole. Current thesis work by Beierl and Tschirley (2017) is exploring UTACC situational awareness and seeks to provide insight on how to accurately test the fire team members' situational awareness throughout execution of a mission. Their work will provide the framework for future testing of UTACC's HMI system.

E. CHAPTER CONCLUSION

Instituting change in any bureaucratic organization, let alone the Marine Corps, is a daunting task. For change to be successful, minimizing disturbance to the organization while easing the transition helps facilitate the integration of new ideas. This thought process guided the authors in their decision to nest the UTACC HMI MOEs and MOPs within current MCTL 2.0 tasks. Furthermore, the decision was made to work exclusively within the proposed MCT 5.1.4- *Maintain Two-Way Communications with Autonomous Robotics* task and not modify or add new MOEs and MOPs to currently published tasks. Lastly, defining an accurate testing environment for the evaluation of UTACC's HMI system is a crucial step in effectively applying and validating the MOEs and MOPs proposed in the final tables, and are discussed in Chapter V.

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V. SUMMARIZING RESULTS AND RECOMMENDATIONS FOR FURTHER RESEARCH

This chapter provides a summary of the authors' research results, broken down by the type of communication requiring evaluation. Additionally, limitations of the resulting tables are discussed which, the authors believe, will require further research and development as the UTACC program progresses. Lastly, future research topics are recommended to drive UTACC closer to integration in the Marine Corps writ large.

A. SUMMARIZING RESULTS

1. MOP and MOE Final Tables

As discussed in previous chapters, the MOEs and MOPs required to evaluate the effectiveness of the HMI communication were broken down into sub-tasks subordinate to the recommended MCT 5.1.4. The next sections will discuss each of these sub-tasks (originally shown in Table 9) in more depth.

The following tables will focus on the identification of team members by UTACC and communication that is human-UTACC and UTACC-human. The authors did not recommend either human-human or UTACC-UTACC MOEs/MOPs as it was outside of the scope of this thesis.

a. MCT 5.1.4.1—Identification of Team Members

Table 10 depicts the MOPs associated with MCT 5.1.4.1. In order to evaluate the MOPs listed, the authors created additional sub-tasks with their own MOPs as depicted in Tables 11, 12, and 13. By assessing MCTs 5.1.4.1.1, 5.1.4.1.2, and 5.1.4.1.3, MCT 5.1.4.1 will be evaluated as a whole.

Table 10. MCT 5.1.4—Identification of Team Members

5.1.4.1	Metric	Identification of Team Members
M1	Percent	Of time UTACC can identify fire team members
M2	Percent	Of modalities UTACC can successfully use to identify fire team members
M3	Distance	Between team members during successful identification

Table 11. MCT 5.1.4.1.1—Visual Identification of Team Members

5.1.4.1.1	Metric	Visual Identification of Team Members
M1	Percent	Of fire team members UTACC can identify visually
M2	Percent	Of time UTACC can visually identify the primary human (fire team leader)
M3	Time	To visually identify the primary human (fire team leader)

Table 12. MCT 5.1.4.1.2—Audible Identification of Team Members

5.1.4.1.2	Metric	Audible Identification of Team Members
M1	Percent	Of fire team members UTACC can identify audibly
M2	Percent	Of time UTACC can audibly identify the primary human (fire team leader)
M3	Time	To audibly identify the primary human (fire team leader)

Table 13. MCT 5.1.4.1.3—Electromagnetic Identification of Team Members

5.1.4.1.3	Metric	Electromagnetic Identification of Team Members
M1	Percent	Of fire team members UTACC can identify electromagnetically
M2	Percent	Of time UTACC can electromagnetically identify the primary human (fire team leader)
M3	Time	To electromagnetically identify the primary human (fire team leader)

In order to measure the effectiveness of UTACC in identifying the team members, and specifically identifying the team leader, the authors separated the task of identification into the modalities that were discussed in Chapter II. The key factors measured are the ability for UTACC to identify the team leader, the time it takes UTACC to identify the team leader, and the ability for UTACC to identify other members of the team.

b. MCT 5.1.4.2—Explicit Human-Robot Communication

MCT 5.1.4.2 pertains to all communication originating from the human and directed to UTACC. Tables 14–18 depict the MCTs along with their respective MOPs associated with evaluating the effectiveness of explicit human-UTACC communication.

In order to measure the effectiveness of the communication, the authors ensured that the following questions would be answered through evaluation:

- Did UTACC receive the message?
- Did UTACC relay the message?
- Did the human verify UTACC's relay?

Through answering the above questions in each of the modalities, the authors believe that the effectiveness of human-UTACC communication can be effectively measured and evaluated.

Table 14. MCT 5.1.4.2—Explicit Human-Initiated Communication

5.1.4.2	**Metric**	**Explicit Human-Initiated Communication**
M1	Percent	Of successful human-initiated messages
M2	Percent	Of successful human-initiated messages on first transmission
M3	Percent	Of modalities able to be used in acheiving successful human-initiated messages
M4	Percent	Of modalities able to be used in acheiving successful human-initiated messages on first transmission

Table 15. MCT 5.1.4.2.1—Visual Human-Initiated Communication

5.1.4.2.1	Metric	Visual Human-Initiated Communication
M1	Percent	Of visual messages UTACC received
M2	Percent	Of visual messages UTACC received correctly
M3	Percent	Of visual messages UTACC received correctly on first transmission
M4	Percent	Of visual messages UTACC relayed correctly
M5	Time	For UTACC to relay correctly from time of initial transmission
M6	Percent	Of UTACC relayed messages understood by human
M7	Distance	Between human and UTACC during messaging

Table 16. MCT 5.1.4.2.2—Audible Human-Initiated Communication

5.1.4.2.2	Metric	Audible Human-Initiated Communication
M1	Percent	Of audible messages UTACC received
M2	Percent	Of audible messages UTACC received correctly
M3	Percent	Of audible messages UTACC receives correctly on first transmission
M4	Percent	Of audible messages UTACC relays correctly
M5	Time	For UTACC to relay correctly from time of initial transmission
M6	Percent	Of UTACC relayed messages understood by human
M7	Distance	Between human and UTACC during messaging

Table 17. MCT 5.1.4.2.3—Electromagnetic Human-Initiated Communication

5.1.4.2.3	Metric	Electromagnetic Human-Initiated Communication
M1	Percent	Of electromagnetic messages UTACC received
M2	Percent	Of electromagnetic messages UTACC received correctly
M3	Percent	Of electromagnetic messages UTACC receives correctly on first transmission
M4	Percent	Of electromagnetic messages UTACC relays correctly
M5	Time	For UTACC to relay correctly from time of initial transmission
M6	Percent	Of UTACC relayed messages understood by human
M7	Distance	Between human and UTACC during messaging

Table 18. MCT 5.1.4.2.4—Haptic Human-Initiated Communication

5.1.4.2.4	Metric	Haptic Human-Initiated Communication
M1	Percent	Of haptic messages UTACC received
M2	Percent	Of haptic messages UTACC received correctly
M3	Percent	Of haptic messages UTACC receives correctly on first transmission
M4	Percent	Of haptic messages UTACC relays correctly
M5	Time	For UTACC to relay correctly from time of initial transmission
M6	Percent	Of UTACC relayed messages understood by human
M7	Distance	Between human and UTACC during messaging

c. MCT 5.1.4.3—Explicit Robot-Human Communication

Similar to how MCT 5.1.4.2 pertains to human-initiated communication, MCT 5.1.4.3 pertains to communication originated by UTACC. Tables 19–23 show the corresponding MCTs and their MOPs which can be used to evaluate the effectiveness of the UTACC-initiated communications.

Just as in the previous section, three questions must be answered to verify effective communication:

- Did the human receive the message?
- Did the human acknowledge the message?
- Did UTACC understand the acknowledgement?

The difference between these and the previous sections' questions pertain to UTACC relaying as opposed to the human acknowledging the original message. The distinction between these two ideas is that UTACC, just like a human member of the fire team, needs to relay the message to other team members; those members will then continue the relay process until the entire team is notified. Although the human will also be relaying the message to other team members, the MOP for testing UTACC is how well it can track the human's acknowledgement, not the ability of the human to conduct the relay. The human relaying the message to another human is beyond the scope of this thesis.

Table 19. MCT 5.1.4.3—Explicit Robot-Initiated Communication

5.1.4.3	Metric	Explicit Robot-Initiated Communication
M1	Percent	Of successful robot-initiated messages
M2	Percent	Of successful robot-initiated messages on first transmission
M3	Percent	Of modalities able to be used in acheiving successful robot-initiated messages
M4	Percent	Of modalities able to be used in acheiving successful robot-initiated messages on first transmission

Table 20. MCT 5.1.4.3.1—Visual Robot-Initiated Communication

5.1.4.3.1	**Metric**	**Visual Robot-Initiated Communication**
M1	Percent	Of visual messages human received
M2	Percent	Of visual messages human received correctly
M3	Percent	Of visual messages human received correctly on first transmission
M4	Percent	Of human acknowledgements understood by UTACC
M5	Percent	Of human acknowledgements understood by UTACC on first acknowledgement
M6	Time	For human to acknowledge correctly from time of initial transmission
M7	Distance	Between human and UTACC during messaging

Table 21. MCT 5.1.4.3.2—Audible Robot-Initiated Communication

5.1.4.3.2	**Metric**	**Audible Robot-Initiated Communication**
M1	Percent	Of audible messages human received
M2	Percent	Of audible messages human received correctly
M3	Percent	Of audible messages human received correctly on first transmission
M4	Percent	Of human acknowledgements understood by UTACC
M5	Percent	Of human acknowledgements understood by UTACC on first acknowledgement
M6	Time	For human to acknowledge correctly from time of initial transmission
M7	Distance	Between human and UTACC during messaging

Table 22. MCT 5.1.4.3.3—Electromagnetic Robot-Initiated Communication

5.1.4.3.3	**Metric**	**Electromagnetic Robot-Initiated Communication**
M1	Percent	Of electromagnetic messages human received
M2	Percent	Of electromagnetic messages human received correctly
M3	Percent	Of electromagnetic messages human received correctly on first transmission
M4	Percent	Of human acknowledgements understood by UTACC
M5	Percent	Of human acknowledgements understood by UTACC on first acknowledgement
M6	Time	For human to acknowledge correctly from time of initial transmission
M7	Distance	Between human and UTACC during messaging

Table 23. MCT 5.1.4.3.4—Haptic Robot-Initiated Communication

5.1.4.3.4	**Metric**	**Haptic Robot-Initiated Communication**
M1	Percent	Of haptic messages human cognitively received
M2	Percent	Of haptic messages human cognitively received on first transmission
M3	Percent	Of human acknowledgements understood by UTACC
M4	Percent	Of human acknowledgements understood by UTACC on first acknowledgement
M5	Time	For human to acknowledge correctly from time of initial transmission
M6	Distance	Between human and UTACC during messaging

2. Limitations of MOP and MOE Tables

The authors identified three main limitations while developing these MOEs and MOPs. First, due to changing environment and conditions, the thresholds for testing will not be static. Given a testing scenario and in line with the proposed MCTs, a range of thresholds will need to be developed to realistically assess the effectiveness and performance of the communication modalities. Second, the electromagnetic modality is a rapidly evolving method of communication. As a result, rather than drive the requirements process, it was left intentionally vague to serve as a guideline for future development, testing, and implementation.

Third, operating UTACC often requires rapid tactical adaptation. From an HMI perspective, this rapid adaptation means the modality used for communication, and thus the interface used, changes during a mission. Thus, an MOP might show that a given set of devices work, but the team leader, for tactical reasons, may not choose that method. Therefore, determining the overall MOP of communications between Marines and machines is made more complicated due to the dynamic nature of tactical operations. Thus, several modalities may need to be used during a mission. Selection of the correct modality for communication based on the tactical situation is an area ripe for further research.

B. RECOMMENDATIONS FOR FURTHER RESEARCH

a. MOE/MOP Tables for Situational Awareness Sensor Suite

During DT1, UTACC relied on GPS data from fire team members to form its situational awareness with respect to its position in the fire team. While GPS was chosen to facilitate timely testing, issues brought on by localization error highlighted a critical area requiring future research. This thesis developed MOE/MOP tables for the sensors used in fire team communications with UTACC. Concurrent to this thesis is research by Beierl and Tschirley (2017) on UTACC situational awareness. However, a fundamental area has yet to be researched: MOEs and MOPS used to assess situational awareness of UTACC and the fire team members. This thesis, in conjunction with Beierl and Tschirley's (2017), provides the framework for the next logical step in Marine-machine teaming: developing MOE/MOP tables to assess UTACC's situational awareness sensor suite, as well as developing MOE/MOP tables to assess the cognitive load on fire team member's situational awareness brought on by the incorporation of new sensors.

b. MOE/MOP Tables for Sensor Suite Supporting Targeting Data

As mentioned by Kirkpatrick and Rushing (2016), during LTA-2, networked UTACC sensors were used semi-autonomously to generate targeting data which was then relayed to a notional strike platform for follow-on execution of the strike package (Kirkpatrick & Rushing, 2016). They go on to recommend research that explores UTACC's role in supporting air-to-surface targeting. In conjunction with this research, establishing MOEs and MOPs for the target acquisition sensor suite needs to be researched concurrently. MCRP 3-16.1.A *Tactics, Techniques, And Procedures for Field Artillery Target Acquisition* serves as starting point for both of these areas.

c. Changing the Role/Scale of UTACC

This thesis explored and created MOEs and MOPs to assist in the selection of sensors used for human-machine communication at the fire team level. Furthermore, the authors constrained themselves to UTACC operating in the role of automatic rifleman in order to remain consistent with concurrent research. Because the authors limited the relationship to the automatic rifleman within a fire team, MOEs and MOPs focused specifically on that relationship. However, as UTACC progresses, MOE/MOP tables will need to be established to help developers evaluate relationships such as robot-robot communication, robot-higher (squad, company, etc.) communication, or UTACC communicating directly with a node or database informing the common operating picture.

d. Doctrinal Changes with the Addition of UTACC

As mentioned in Chapter II, this thesis, paired with Kirkpatrick and Rushing's (2016) work, will aid in the creation of new doctrine inclusive of the autonomous systems in line with both EF21 and the Marine Corps Operating Concept. Current doctrine establishes TTPs based on the firepower provided by the automatic rifleman. However, the technological advantages afforded a Marine-machine fire team will certainly require an evolution of current fire team-level TTPs to maximize UTACC's potential. Exploring and researching what these doctrinal changes will look like is another step forward in developing the UTACC program.

C. CHAPTER CONCLUSION

MCWL's UTACC program seeks to address the challenges encountered in the complex battlefield environment of the twenty-first century with the integration of Marines and autonomous machines at the fire team level. This thesis explored a small piece of that equation: communication interface requirements between man and machine. While the communication interfaces are a fraction of the overall UTACC problem set, choosing the right interfaces to achieve man-machine communication is essential for the continued success of the Marine-machine teaming concept. The authors of this thesis established recommended MOEs/MOPs for evaluating the communication interfaces required for Marine-machine communication as well as where they fit within the MCTL. Furthermore, recommended future research topics will continue to drive the progress of the UTACC program. While still in the early stages of development, the UTACC program has the potential to fundamentally shift the way mankind approaches warfare in the years to come.

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APPENDIX A. MCT 5.1.4 *MAINTAIN TWO-WAY COMMUNICATION WITH AUTONOMOUS ROBOTICS* AND FIRST LEVEL SUB-TASKS

This shows the highest level breakdown of MCT 5.1.4.

5.1.4	**Metric**	**Maintain Two-Way Communication with Autonomous Robotics**
M1	Percent	Of successfully communicated messages
M2	Percent	Of successfully communicated messages on first transmission
M3	Distance	Between team members during successful communication
5.1.4.1	**Metric**	**Identification of Team Members**
M1	Percent	Of time UTACC can identify fire team members
M2	Percent	Of modalities UTACC can successfully use to identify fire team members
M3	Distance	Between team members during successful identification
5.1.4.2	**Metric**	**Explicit Human-Initiated Communication**
M1	Percent	Of successful human-initiated messages
M2	Percent	Of successful human-initiated messages on first transmission
M3	Percent	Of modalities able to be used in acheiving successful human-initiated messages
M4	Percent	Of modalities able to be used in acheiving successful human-initiated messages on first transmission
5.1.4.3	**Metric**	**Explicit Robot-Initiated Communication**
M1	Percent	Of successful robot-initiated messages
M2	Percent	Of successful robot-initiated messages on first transmission
M3	Percent	Of modalities able to be used in acheiving successful robot-initiated messages
M4	Percent	Of modalities able to be used in acheiving successful robot-initiated messages on first transmission

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APPENDIX B. MCT 5.1.4.1 *IDENTIFICATION OF TEAM MEMBERS* AND SUB-TASKS

This shows the highest level breakdown of MCT 5.1.4.1.

5.1.4.1	**Metric**	**Identification of Team Members**
M1	Percent	Of time UTACC can identify fire team members
M2	Percent	Of modalities UTACC can successfully use to identify fire team members
M3	Distance	Between team members during successful identification
5.1.4.1.1	**Metric**	**Visual Identification of Team Members**
M1	Percent	Of fire team members UTACC can identify visually
M2	Percent	Of time UTACC can visually identify the primary human (fire team leader)
M3	Time	To visually identify the primary human (fire team leader)
5.1.4.1.2	**Metric**	**Audible Identification of Team Members**
M1	Percent	Of fire team members UTACC can identify audibly
M2	Percent	Of time UTACC can audibly identify the primary human (fire team leader)
M3	Time	To audibly identify the primary human (fire team leader)
5.1.4.1.3	**Metric**	**Electromagnetic Identification of Team Members**
M1	Percent	Of fire team members UTACC can identify electromagnetically
M2	Percent	Of time UTACC can electromagnetically identify the primary human (fire team leader)
M3	Time	To electromagnetically identify the primary human (fire team leader)

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APPENDIX C. MCT 5.1.4.2 *EXPLICIT HUMAN-ROBOT COMMUNICATION* AND SUB-TASKS

This shows the highest level breakdown of MCT 5.1.4.2.

5.1.4.2	**Metric**	**Explicit Human-Initiated Communication**
M1	Percent	Of successful human-initiated messages
M2	Percent	Of successful human-initiated messages on first transmission
M3	Percent	Of modalities able to be used in acheiving successful human-initiated messages
M4	Percent	Of modalities able to be used in acheiving successful human-initiated messages on first transmission
5.1.4.2.1	**Metric**	**Visual Human-Initiated Communication**
M1	Percent	Of visual messages UTACC received
M2	Percent	Of visual messages UTACC received correctly
M3	Percent	Of visual messages UTACC received correctly on first transmission
M4	Percent	Of visual messages UTACC relayed correctly
M5	Time	For UTACC to relay correctly from time of initial transmission
M6	Percent	Of UTACC relayed messages understood by human
M7	Distance	Between human and UTACC during messaging
5.1.4.2.2	**Metric**	**Audible Human-Initiated Communication**
M1	Percent	Of audible messages UTACC received
M2	Percent	Of audible messages UTACC received correctly
M3	Percent	Of audible messages UTACC receives correctly on first transmission
M4	Percent	Of audible messages UTACC relays correctly
M5	Time	For UTACC to relay correctly from time of initial transmission
M6	Percent	Of UTACC relayed messages understood by human
M7	Distance	Between human and UTACC during messaging
5.1.4.2.3	**Metric**	**Electromagnetic Human-Initiated Communication**
M1	Percent	Of electromagnetic messages UTACC received
M2	Percent	Of electromagnetic messages UTACC received correctly
M3	Percent	Of electromagnetic messages UTACC receives correctly on first transmission
M4	Percent	Of electromagnetic messages UTACC relays correctly
M5	Time	For UTACC to relay correctly from time of initial transmission
M6	Percent	Of UTACC relayed messages understood by human
M7	Distance	Between human and UTACC during messaging
5.1.4.2.4	**Metric**	**Haptic Human-Initiated Communication**
M1	Percent	Of haptic messages UTACC received
M2	Percent	Of haptic messages UTACC received correctly
M3	Percent	Of haptic messages UTACC receives correctly on first transmission
M4	Percent	Of haptic messages UTACC relays correctly
M5	Time	For UTACC to relay correctly from time of initial transmission
M6	Percent	Of UTACC relayed messages understood by human
M7	Distance	Between human and UTACC during messaging

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APPENDIX D. MCT 5.1.4.3 *EXPLICIT ROBOT-HUMAN COMMUNICATION* AND SUB-TASKS

This shows the highest level breakdown of MCT 5.1.4.3.

5.1.4.3	**Metric**	**Explicit Robot-Initiated Communication**
M1	Percent	Of successful robot-initiated messages
M2	Percent	Of successful robot-initiated messages on first transmission
M3	Percent	Of modalities able to be used in acheiving successful robot-initiated messages
M4	Percent	Of modalities able to be used in acheiving successful robot-initiated messages on first transmission
5.1.4.3.1	**Metric**	**Visual Robot-Initiated Communication**
M1	Percent	Of visual messages human received
M2	Percent	Of visual messages human received correctly
M3	Percent	Of visual messages human received correctly on first transmission
M4	Percent	Of human acknowledgements understood by UTACC
M5	Percent	Of human acknowledgements understood by UTACC on first acknowledgement
M6	Time	For human to acknowledge correctly from time of initial transmission
M7	Distance	Between human and UTACC during messaging
5.1.4.3.2	**Metric**	**Audible Robot-Initiated Communication**
M1	Percent	Of audible messages human received
M2	Percent	Of audible messages human received correctly
M3	Percent	Of audible messages human received correctly on first transmission
M4	Percent	Of human acknowledgements understood by UTACC
M5	Percent	Of human acknowledgements understood by UTACC on first acknowledgement
M6	Time	For human to acknowledge correctly from time of initial transmission
M7	Distance	Between human and UTACC during messaging
5.1.4.3.3	**Metric**	**Electromagnetic Robot-Initiated Communication**
M1	Percent	Of electromagnetic messages human received
M2	Percent	Of electromagnetic messages human received correctly
M3	Percent	Of electromagnetic messages human received correctly on first transmission
M4	Percent	Of human acknowledgements understood by UTACC
M5	Percent	Of human acknowledgements understood by UTACC on first acknowledgement
M6	Time	For human to acknowledge correctly from time of initial transmission
M7	Distance	Between human and UTACC during messaging
5.1.4.3.4	**Metric**	**Haptic Robot-Initiated Communication**
M1	Percent	Of haptic messages human cognitively received
M2	Percent	Of haptic messages human cognitively received on first transmission
M3	Percent	Of human acknowledgements understood by UTACC
M4	Percent	Of human acknowledgements understood by UTACC on first acknowledgement
M5	Time	For human to acknowledge correctly from time of initial transmission
M6	Distance	Between human and UTACC during messaging

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LIST OF REFERENCES

Beierl, C. & Tschirley, D. R. (2017). *Unmanned Tactical Autonomous Control and Collaboration (UTACC) situational awareness*. Manuscript submitted for publication.

Blanchard, B. S. (2008). *System engineering management* (4th ed.). Hoboken, NJ: John Wiley and Sons.

Blanchard, B. S. & Blyler, J. E. (2016). *System engineering management* (5th ed.). Hoboken, NJ: John Wiley and Sons.

Buckler, J., & Roth, B. (2016). *Unmanned tactical autonomous control and collaboration (UTACC) unmanned aerial vehicle analysis of alternatives* (Master's thesis). Naval Postgraduate School. Retrieved from Calhoun http://calhoun.nps.edu/handle/10945/48586

Calinon, S., Evrard, P., Gribovskaya, E., Billard, A., & Kheddar, A. (2009, June). Learning collaborative manipulation tasks by demonstration using a haptic interface. In *International Conference on Advanced Robotics, 2009* (pp. 1-6).

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

Chenoweth, C., & Wilcox, M. D. (2017). *Unmanned Tactical Autonomous Control and Collaboration (UTACC) immediate actions*. Manuscript submitted for publication.

DAU. (n.d.). Critical Operational Issue (COI) / Critical Operational Issue Criteria (COIC). Retrieved April 26, 2017, from https://dap.dau.mil/glossary/pages/1707.aspx

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

DOT&E. (n.d.). Mission focused evaluation – Guidance. Retrieved April 26, 2017, from http://www.dote.osd.mil/docs/TempGuide3/Mission_Focused_Evaluation_Guidance_3.0.pdf

Fong, T. W., Conti, F., Grange, S., & Baur, C. (2001, March). Novel interfaces for remote driving: gesture, haptic, and PDA. In *Intelligent Systems and Smart Manufacturing* (pp. 300–311). Bellingham, WA: International Society for Optics and Photonics.

Global Security. (n.d.). Marine Corps policy documents. Retrieved May 31, 2017, from http://www.globalsecurity.org/military/library/policy/usmc/index.html

Gold, K. (2009). An information pipeline model of human-robot interaction. *2009 4th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*,85–92.

Jameson, S., Franke, J., Szczerba, R., & Stockdale, S. (2005). Collaborative autonomy for manned/unmanned teams. In *Annual Forum Proceedings-American Helicopter Society 61*(2), 1673. Retrieved from http://www.atl.lmco.com/papers/1283.pdf

Johnson, M. J. (2014). *Coactive design: Designing support for interdependence in human-robot teamwork* (Doctoral dissertation). TU Delft, Delft University of Technology, the Netherlands. Retrieved from http://www.sim.informatik.tu-darmstadt.de/fileadmin/user_upload/Duran-etal_IHMC.pdf

Johnson, M., Bradshaw, J., Feltovich, P., Jonker, C., van Riemsdijk, M., & Sierhuis, M. (2014). Coactive design: Designing support for interdependence in joint activity. *Human Robot-Interaction*, *3*(1). Retrieved from http://humanrobotinteraction.org/journal/index.php/HRI/article/view/173

Johnson, M., Bradshaw, J., Feltovich, P., Jonker, C., van Riemsdijk, B., & Sierhuis, M. (2011). The fundamental principle of coactive design: Interdependence must shape autonomy. In M. De Vos, N. Fornara, J. Pitt, & G. Vouros (Eds.), *Coordination, Organizations, Institutions, and Norms in Agent Systems VI* (Vol. 6541, pp. 172–191). Berlin: Springer Berlin/Heidelberg. Retrieved from http://link.springer.com/chapter/10.1007/978-3-642-21268-0_10

Kirkpatrick, T. D., & Rushing, E. P. (2016). *Unmanned tactical autonomous control and collaboration measures of performance and measures of effectiveness.* (Master's thesis). Retrieved from Calhoun http://calhoun.nps.edu/handle/10945/50568

Kott, A., Alberts, D., Zalman, A., Shakarian, P., Maymi, F., Wang, C., & Qu, G. (2015). *Visualizing the tactical ground battlefield in the year 2050: Workshop report* (No. ARL-SR-0327). Adelphi, MD: Army Research Lab.

National Research Council. (2014). *Complex operational decision making in networked systems of humans and machines: a multidisciplinary approach*. Washington, DC: National Academies Press.

Naval Postgraduate School & Marine Corps Warfighting Laboratory. (2016). Statement of work (SOW): Concept of operations for unmanned tactical autonomous control and collaboration project. Unpublished manuscript.

Norman, D., Draper, W. (1986). *User Centered System Design.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Perzanowski, D., Adams, W., Schultz, A., & Marsh, E. (2000). Towards seamless integration in a multi-modal interface. *Workshop on Interactive Robotics and Entertainment (WIRE 2000)*. Retrieved from http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA434973

Rice, T., Chhabra, T., & Keim, E. (2015). *Unmanned tactical autonomous control and collaboration (UTACC) concept of operations* (Master's thesis). Retrieved from Calhoun https://calhoun.nps.edu/handle/10945/45738EF21

Safariland Group. (n.d.). Tactical throat microphone headset set. Retrieved April 26, 2017, from https://www.safariland.com/products/comms-and-hearing-protection/headsets/throat-microphone-headsets/tactical-throat-microphone-headset-set-TTMK3_D.html

Schätzle, S., Ende, T., Wüsthoff, T., Preusche, C. (2010, September). VibroTac: An ergonomic and versatile usable Vibrotactile feedback device. In *RO-MAN, 2010 IEEE* (pp. 670-675).

Shattuck, L. G., & Lewis Miller, N. (2006). Extending naturalistic decision making to complex organizations: A dynamic model of situated cognition. *Organization Studies, 27*(7), 989–1009.

Singer, P. W. (2009). *Wired for war: The robotics revolution and conflict in the 21st century*. New York, NY: Penguin Publishing.

Soldier Systems. (n.d.). Black Diamond introduces new tactical computer system Retrieved April 26, 2017, from http://soldiersystems.net/2011/05/31/black-diamond-introduces-new-tactical-computer-system/

Traum, D., Rickel, J., Gratch, J., & Marsella, S. (2003, July). Negotiation over tasks in hybrid human-agent teams for simulation-based training. In *Proceedings of the second international joint conference on Autonomous agents and multiagent systems* (pp. 441–448). ACM.

U.S. Joint Chiefs of Staff. (2011). *Joint Publication 3-0: Joint operations*. Washington, DC: Department of Defense.

U.S. Joint Chiefs of Staff. (2017). *Joint Publication 3-0: Joint operations*. Washington, DC: Department of Defense.

U.S. Joint Chiefs of Staff Joint Staff J-7. (2011). *Commander's handbook for assessment planning and execution V 1.0.* Suffolk, VA: U.S. Joint Chiefs of Staff Joint Staff J-7.

U.S. Department of Health and Human Services. (2015, February). *User-Centered Design Basics*. Retrieved from https://www.usability.gov/what-and-why/user-centered-design.html

United States Army. (1987). *Visual Signals.* Washington, DC: Headquarters, Department of the Army.

United States Marine Corps. (1996). MCRP 3-16.1.A: *Tactics, techniques, and procedures for field artillery target acquisition*. Washington, DC: Department of the Navy.

United States Marine Corps. (2002). *Marine Rifle Squad*. Washington, DC: Department of the Navy.

United States Marine Corps. (2014). *Expeditionary Force 21*. Washington, DC: Headquarters Marine Corps.

United States Marine Corps. (2016). *Marine Corps operating concept*. Washington, DC: Department of the Navy.

United States Marine Corps. (2011). *MCDP 1: Warfighting.* Washington, DC: Department of the Navy.

United States Marine Corps. (n.d.) Marine Corps Task List Branch (MID/MCTL) Capabilities Development Directorate DC, CD&I. Retrieved April 27, 2017, from http://www.mccdc.marines.mil/Units/Marine-Corps-Task-List/

Zach, M. (2016). *Unmanned tactical autonomous control and collaboration (UTACC) coactive design* (Master's thesis). Retrieved from Calhoun http://hdl.handle.net/10945/49417

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