A Mixed Initiative Human-Robots Team Performance Assessment System For Use in Operational and Training Environments

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ABSTRACT

Military forces of the future will use mixed manned and unmanned forces for a broad variety of functions. Measurement of overall effectiveness in these mixed initiative systems will be essential in order to achieve optimal system performance levels. Behavioral measures of both human and unmanned performance obtained in system simulations or in live exercises will be used to continuously diagnose performance and identify required areas of training requirements. Likewise, specialized training will be necessary in order to leverage the complementary cognitive functions of human and machine to forge fighting entities and units with capabilities superior to those of humans or machines in isolation. Our team is currently developing a Mixed Initiative Team Performance Assessment System (MITPAS) consisting of a methodology, tools and procedures to measure the performance of mixed manned and unmanned teams in both training and real world operational environments. The work is being performed under SBIR Phase I and II contracts administered by RDECOM/STTC, Orlando, FL. Our objective is to provide a scalable turnkey MITPAS software system integrated with simulation and training environments, utilizing COTS HLA data logging tools and containing protocols for evaluation of various manned/unmanned team configurations in selected event-based scenarios. This paper describes our in-progress development of a underlying Multi-Dimensional Performance Model, our preliminary MITPAS architecture and our Use Case Scenario based experimental and evaluation plan, as well as our ideas for future applications of the completed MITPAS.

KEYWORDS: *mixed initiative teams, human-robot performance assessment, robotic training systems*

1. INTRODUCTION

Mixed initiative introduces a new and unique aspect to the psychology of team performance: the interaction of two cognitive systems -- human and autonomous unmanned robot. In addition to the critical performance factors associated with human teams -- which include information exchange, communication, supporting behavior and team leadership -- the mixed manned/unmanned team adds a number of challenging new dimensions. Foremost among these is the ability of the human team to manage, predict, collaborate and develop trust with unmanned systems that may sometimes exhibit fuzzy responses in unstructured and unpredictable environments [1] [2] [3] [4] [8] [9].

The critical challenge in our work has been to develop system-specific measures of behavior on which to base assessment of the mixed initiative team performance. Such measures must be unique to the information and decision environment associated with human-robotic teams and to directly link together behavioral processes important to mixed manned/unmanned tactical outcomes. The measures need to provide feedback for skill improvement in collaboration as well as adaptation to stress and workload, and they should help define the training needs themselves.

2. PERFORMANCE MEASURES

Our work on the definition of relevant performance measures began with the realization that future unmanned platforms will have some capability to operate autonomously within the scope of their mission tasking, but will be continuously "commanded" by human operators who will each direct the activities of a number of robots. As more is learned about modeling human behavior, increased sophistication in autonomous operations by robotic systems can be expected to reduce dependence on human supervisory controllers. At today's and the near-future state of understanding, however, certain functions are not well supported by automation and can be performed at a much higher level of competence by human beings in collaboration with the robotic entities.

Accordingly, at the performance level there are new human factors issues that require new types of skills and training. These emerge from the nature of the robots as decision-making systems operating in uncertain, unpredictable and unstructured environments. The key new performance issues include:

- Performing supervisory control of robots

- Adapting to variations in the level autonomy the robots exhibit in response to environmental and task variables
- Varying task allocation to exploit the distinct advantages of the human and robotic component (e.g., a robot can endure long mission duration, survive better but may have only about 80% of human cognitive capabilities)
- Monitoring of robots' decisions and actions to maintain to achieve transparency of robot actions
- Overriding robot decisions and actions when necessary
- Helping to solve problems and handle contingencies

Research performed to date on measurement of team training performance has focused on both the individual and team levels [5] [6]. It is recognized that while both process and outcome measures are essential, training feedback mainly comes from process measures. The guiding principles are: (1) measurement and remediation must emphasize processes that are linked to outcomes; and (2) Individual and team levels deficiencies must be distinguished to support the instructional process. In our view these principles are directly applicable to the manned/unmanned team with the addition of another level in the team structure, which we term as the Collective Manned/Unmanned (CMU) level, and which represents the major new dimension that is added to the team task characteristics and structure. Our selection of measuring instruments and speci-fication of associated measurement methodologies thus extends the individual-team matrix of Cannon–Brower [1] to include the present case of collaborative manned/unmanned teams.

3. PERFORMANCE MODEL

The basis of our MITPAS approach has been to develop a Manned/Unmanned Team Multi-Dimensional Performance Model that captures the critical performance attributes of the distinct human and robotic decision and control environment. Figure 1 below provides an overview of the hierarchical structure of the Model's performance dimensions.

The Performance Model we are developing draws on four separate research areas that have been pursued independently in the past but which are being integrated in this project to establish meaningful criteria of overall performance. These research areas are:

- **Psychology of Team Performance** - Human team performance measurement in C3 information environ-ments, performance variables, training evaluation and measuring team related expertise, management of workload and stress.
- **Unmanned Systems** - Principles of establishing performance metrics for autonomous systems
- **Mixed Initiative Systems** – Research and findings on the critical variables which affect human decision and control of autonomous systems
- **War Fighting Behavior** – Observations and measure-ments of combat team performance in war fighting tasks C3 tasks

We have integrated and adapted theories and concepts in these areas to processes associated with manned/unmanned team

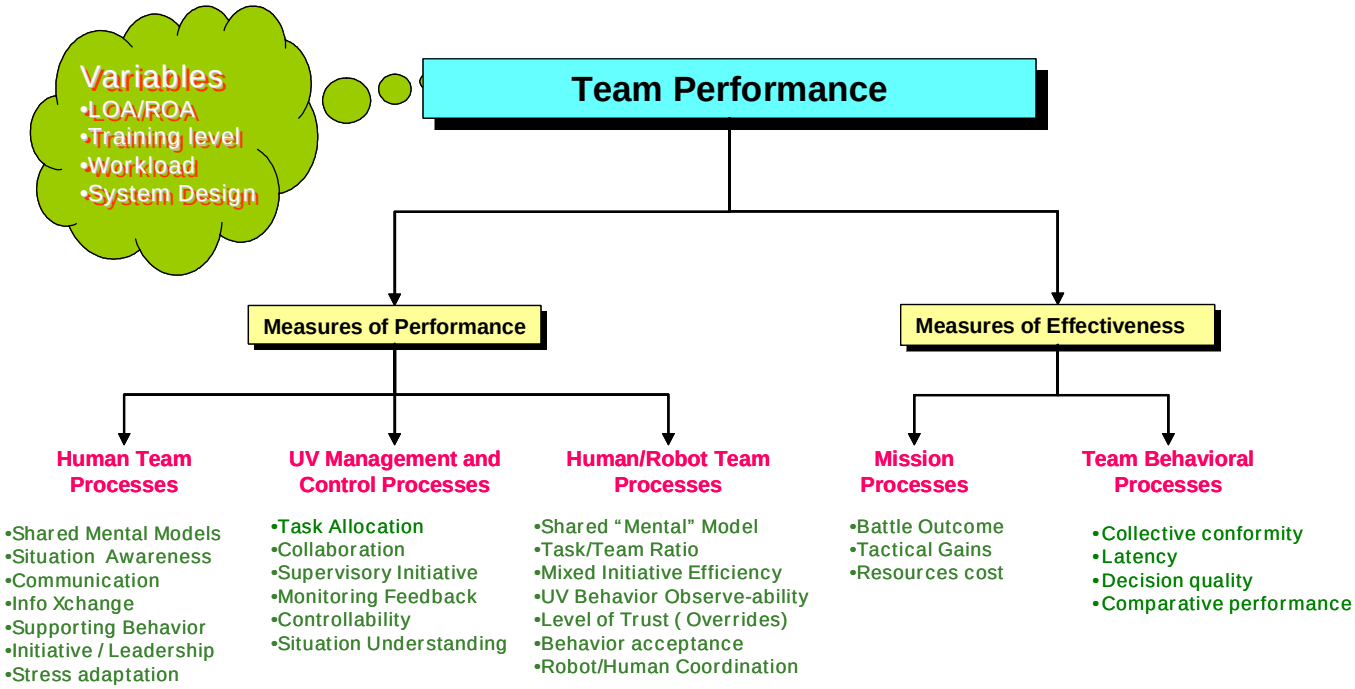

Figure 1 System Performance Model

performance and training. Most critical were variables related to the decision making behavior of the unmanned

systems, such as behavior transparency to the human collaborators, human trust in robot decisions and human abilities to synergize the autonomy of robots so as to add to the capability of the total team. Issues such as behavior prediction, level of autonomy and acceptance of robots actions have also been examined and identified for possible high impact variable on total system performance.

In accord with this approach, we have created a preliminary System Performance Model which captures the critical performance attributes of the distinct process of behavior composition environment. Our objective was to identify the dimensions of performance which contribute to effective outcomes of collaborative manned-unmanned tasks and, in particular, to formulate measures to evaluate training in processes that are unique to the collective team of humans and robots. Accordingly, we have built a taxonomy of specific processes which can be decomposed into explicit behavioral objectives side-by-side with measures of effectiveness based on actual outcomes. Our focus is on process measures that are closely linked to outcomes, because it is these measures that will provide the feedback necessary for training. The three levels of team processes critical to training evaluation and remediation are: (1) individual human; (2) team human; and (3) collective human/robot team.

We decomposed the processes into these three levels and developed taxonomy of measures for each level. We narrowed the performance measures to the simplest factor structure that adequately cover the dimension of teamwork as was found in previous investigators [2]. The actual Performance Model will consist of a multi-dimensional task process performance schema which will (1) aggregate the performance measures at each level, (2) provide for training feedback at each level, and (3) provide a multi-attribute discriminate function to determine an overall level of proficiency as well as a "pass-fail' score. The weights of the attributes will be established in simulations in which the linkage between specific task performance measures and outcomes can be estimated. There are two main types of measures: Measures of Performance (MOP) and Measures of Effectiveness (MOE); these are defined separately below.

1. Measures of Performance (MOP)

These are observable and derived measures of the operators' task skills, strategies, steps or procedures used to accomplish the task. They consist of the cognitive and interactive processes of the individual and team in collaborating together and controlling the robotic entities in a coordinate manner. MOP evaluates the human factor involved in a complex system. MOP was divided into 3 distinct classes of processes dimensions:

- **Human Team Processes** - These processes represent the dimensions of the human team interaction
- **UV Management and Control Processes** - These processes represent the tasks associated with real time control and monitoring of the autonomous entities
- **Human/Robot Team Processes** - These processes represent the dimensions of the human interaction with the robotic elements

2. Measures of Effectiveness (MOE)

These measure the "goodness' of the composed behavior in quality and the execution of war-fighting tasks. MOEs are influenced by much more than human performance. These measures also contain variance accounted for by system design, the surrounding environment and luck [6]. The measure consists of the following dimensions

- **Mission Effectiveness** - Observable measures of the success of the mission as determined by objective military criteria.
- **Behavioral Effectiveness** - Measures of the dimension of behavioral effectiveness of the system in the battlefield

We anticipate that only a relevant and/or application-specific subset of all possible performance measures will be used in the turnkey MITPAS because: (1) some of the measures may be correlated; and (2) the selected ones will require assurance of high diagnostic value, which is referred to as *discrimination validity*, in the particular situation. In our future laboratory tests we plan to reduce the possible set of measures to a manageable subset.

4. MITPAS FUNCTIONAL REQUIREMENTS

Our plan is to implement MITPAS as a turnkey software package incorporating three major capabilities:

- Tools to set identify and specify key events that must be included in an exercise in order to stimulate execution of actions by participants that are the targets of performance measurements;
- Tools to capture data during the conduct of the exercise, including automated extraction from data loggers and formats for observational inputs from observers and controllers;
- Analytical tools to combine the data collected and produce quantitative measures of the performance and effectiveness of the human-robotic team(s) being studied;
- Report generation tools to allow researchers and trainers to produce diagnostic and prescriptive arrays of the analytic products.

We will also build initial tactical and technical databases, using proposed FCS tables of organization and equipment and similar documents from other UV programs, databases.

Figure 2 below diagrams the MITPAS system and its place within the training and evaluation environments. The Figure focuses on MITPAS as an adjunct to the existing distributed interactive training environment, specifically the OneSAF Test Bed (OTB), in which it will be developed and initially evaluated. Figure 2 also expands on the normal context diagram conventions to include the internal components of the system as well, highlighting which components interact with which outside entities.

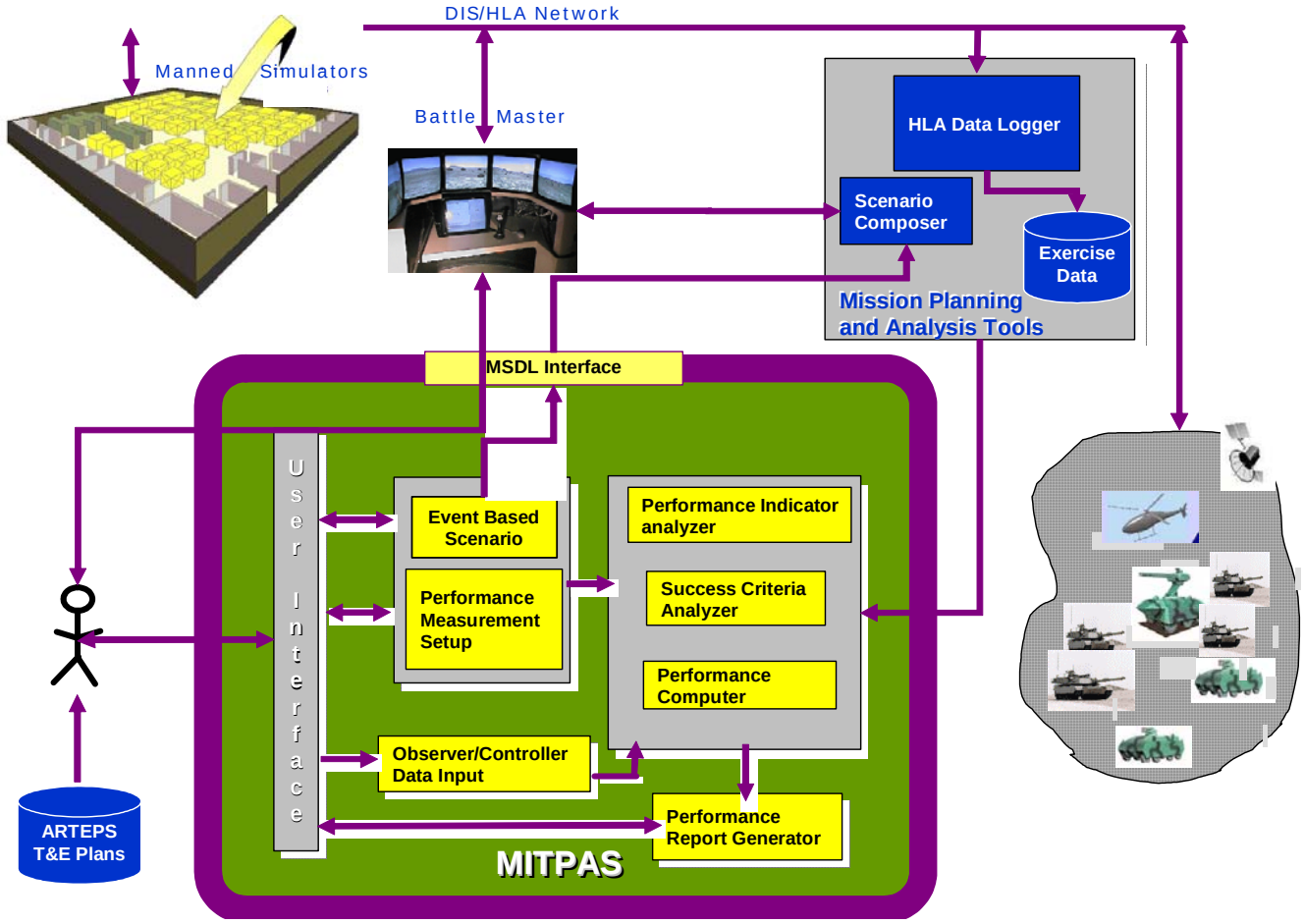

Figure 2 MITPAS Components and Context

In its initial implementation the system will also serve as the environment in which candidate measures and metrics are tested against actual exercise performance in experiments to identify and validate those measures that are most correlated with and predictive of successful tactical performance and battle outcome. We will define the high-level system functions in terms of Use Case Scenarios and Interaction Diagrams for the various types of users as well as for interactions between MITPAS and external systems, such as:

- Military Instructors and systems performance evaluators
- Unit commanders who assign and monitor mission status
- System Designers and Planners

5. MITPAS ARCHITECTURE

In our planned future efforts we will complete and implement the MITPAS software architecture, developing the interfaces with external systems and user interfaces to support identification of scenario requirements, selection of measures, monitoring and data collection, and post-exercise review and analysis. We will also develop the analytical engine within the software, and as the performance measurement algorithms are developed they will be embedded in that component. The development of components will be done iteratively, in a spiral development process, providing an early initial capability for experimentation, and evolving as experiments yield more data about performance and system requirements. In brief, we will implement a MITPAS Prototype System that will:

- Provide a Core Infrastructure for measuring the performance of Mixed-Initiative exercises. The core infrastructure is designed to facilitate the rapid implementation of performance measurement and analysis algorithms as well as to enable integration

with multiple heterogeneous simulation and test environments.

- Implement the specific performance measurement and analysis detailed for the scenario described in this proposal using the Core Infrastructure

Careful consideration will be given to allow the system to be scalable and provide extensive integration capabilities to meet evolving performance assessment requirement over the system life-cycle. Critical to achieving these goals is the use of a modular component-based software architecture which extensively leverages open standards and de-facto standard best practices in distributed system development.

Furthermore, the system will leverage established tools and components which have emerged from prior DoD investment in modeling and simulation as well as independently developed tools for collecting and analyzing data for DIS and HLA. Additional consideration will be given to developing and emerging standards in the training and simulation communities. In particular, the MITPAS Core Infrastructure will be designed to support the Test and Training Enabling Architecture (TENA) under development for PEO STRI as a product of the Foundation Initiative 2010. TENA provides significant improvements on HLA and is designed to be used with embedded training systems and in training ranges.

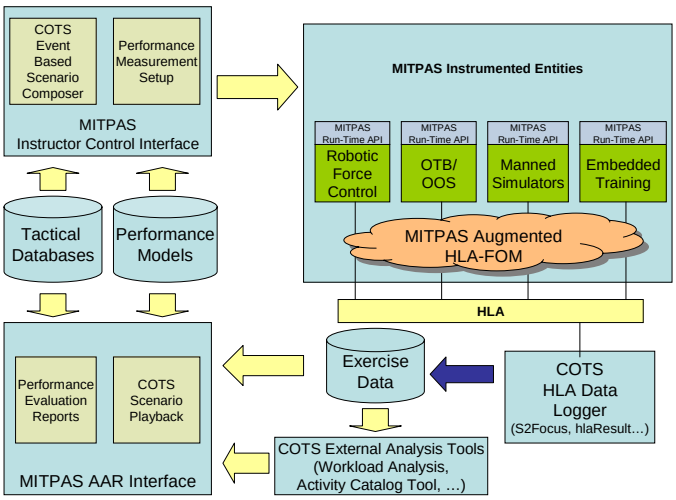

Figure 3 MITPAS Architecture

Figure 3 shows the main MITPAS system architecture. The system is comprised of the following core components:

- MITPAS Instructor Console – An application to set parameters for a given Mixed-Initiative exercise as well as construct a scenario
- MITPAS Instrumentation Run-Time API – A middleware toolkit with APIs in C and Java to enable rapid instrumentation of entities including C4I Systems, simulation systems, and embedded training systems
- HLA Data Logger Interface – A connection to an existing data capture mechanism for capturing and managing data from an HLA data-stream
- MITPAS AAR Interface - An application which implements the analysis and reporting capabilities of the system as well as invocation of Scenario playback
- MITPAS Augmented HLA FOM – Supports capture of additional data such as human interaction events, MITPAS will require augmenting of a particular HLA Federation Object Model to add the additional classes and interactions.

6. Use Case Scenario

We will use scenario-based training trials as the experimental paradigm to identify, refine and validate MITPAS measures. Scenario-based training relies on controlled exercises, or vignettes, in which the target training audience is presented with cues that are similar to those found in the actual task environment and then given performance feedback. In mature training environments such scenarios are developed using training and doctrinal materials such as ARTEPS and Mission Training Plans along with validated performance measures. In the MITPAS project, however, the goal is to identify and validate measures for a type of unit that does not yet exist and for whom no training documents have been developed. Accordingly, we have developed a baseline scenario based on:

- Examination of candidate performance measures
- Study of the Future Combat System 2015 Unit of Action Design
- Sponsor focus on countermine capabilities

Our current MITPAS use-case scenario focuses on a platoon of a Reconnaissance Troop, reinforced with Engineers, which is escorting a convoy in an Iraq-like environment. The platoon employs UGVs, SUGVs, UAVs (Type 3), MULES and an ACRV, which allows for representation of a wide range of robotic capabilities and supports experiments focusing on soldiers controlling individual robots, on those controlling multiple homogeneous or heterogeneous robots, or on a leader controlling mixed human and robotic elements. Our current scenario requires subjects to deal with an improvised explosive device, a traditional minefield, small unit enemy action, casualties, and maintaining communications.

We are able to identify a set of critical control events within the MITPAS scenario that exemplify the type of mixed initiative performance we are trying to assess. In the future these critical events will be further refined in cooperation with our RDECOM PMs. In addition, the final scenario events and candidate performance measures will then mapped to each other to ensure that scenario execution will elicit the actions

that the measures require. Table 1 below shows an initial stage in the process, in which measures are mapped into scenario events based on the current findings. The purpose here is to demonstrate the methodological approach, rather than provide an exhaustive listing, which will form part of the planned future effort.

Table 1 Scenario Events vs. Performance Measures

MEASURE		EVENT																									
		1	1.a	1.b	2	2.a	2.a.1	2.b	2.b.1	3	3.a	3.a.1	3.a.1.a	3.a.2	3.a.2.a	3.b	4	4.a	4.a.1	5	5.a	5.b	6	6.a	6.a.1	6.b	6.b.1
Human Team Processes	Shared Mental Models	X	X	X		X		X	X		X	X	X	X		X	X	X		X	X	X	X	X		X	X
	Situation Awareness	X	X	X		X		X	X		X	X	X	X		X	X	X		X	X	X	X	X		X	X
	Communication	X	X	X		X	X	X	X	X	X	X	X	X		X	X		X	X	X	X	X	X	X	X	X
	Information Exchange	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X
	Supporting Behavior	X	X	X		X		X	X		X	X	X	X		X	X	X		X	X	X	X	X		X	X
	Initiative/ Leadership	X	X	X		X		X	X		X	X	X	X		X	X	X		X	X			X		X	X
	Stress Adaptation	X	X	X		X		X	X		X	X	X	X		X	X	X		X	X			X		X	X
UV Mgmt and Control Processes	Task Allocation	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X
	Collaboration	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X
	Supervisory Initiative	X	X	X		X		X	X		X	X		X		X	X	X		X	X			X		X	X
	Monitoring Feedback	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Controllability	X	X	X		X	X	X	X		X	X		X	X	X	X	X		X	X	X		X		X	X
	Situation Understanding	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

7. Criteria for Success

Our approach to establishing criteria of success will follow the concepts of the Army Training and Evaluation Program (ARTEP), which is the cornerstone program of unit training.

Each ARTEP consists of defined tactical tasks to be performed under specified conditions to a criterion or standard. To determine if the standard is reached, the ARTEP provides evaluators with a list of Task Steps and Performance Measures scored Go, No Go or Not Evaluated. The ratio of subjective Go to No Go marks and the significance of each determine whether the performance standard has been met. While the Rates have evolved over decades to capture virtually all-relevant measures of performance with regard to human collectives, collectives of humans and robots will demand the exercise of additional skills by the human elements. The robots' decisions will not always be transparent to the humans. Human acceptance of these decisions will depend on understanding the robots' capabilities and anticipate robot behavior. The approach was proposed in our Phase I proposal and furtherer analysis validated its applicability and effectiveness.

We will aggregate the individual performance measures into a scoring criterion by starting with selected ARTEPS that can be adapted to human-robotic collectives (using FCS training studies as a guide) and adding additional measures such as the ones discussed above. The single-score-for-a-single-task methodology of ARTEP will be expanded to provide a single score for a collective patterns of tasks We propose a multi-dimensional criterion of performance success, P, that combines the direct performance measures across the various experimental (robot system) variables, as described below:

1. Let x be the pattern of performance measures $x_j = (x_{1j}, x_{2j}, x_{3j}, \ldots, x_{nj})$ under the various conditions, i.e. level of automation, stress, etc marked by the subscript j

The multi-attribute performance score for condition j is:

$$g(x_j) = w_1 x_{1j} + w_1 x_{2j} + w_1 x_{3j} + \ldots + w_n x_{nj},$$

thus

$$g(x_j) = \sum_{i=1}^{n} w_i x_{ij}$$

2. To get a total score cross all conditions the combined score is

$$\sum_{j=1}^{m} g(x_j)$$

3. The combined aggregated score for all performance measures and condition will then be:

$$\text{Total Score } P = \sum_{j=1}^{m} \sum_{i=1}^{n} w_i x_{ij}$$

4. The weights $(w_1, w_2, \ldots, w_n)$ will be determined by testing experiments and expert judgment using a parameter estimation protocol of the type used in trainable pattern recognizers.

We have developed a schema employing a factor analytic approach to reducing and refining the set of measures to reflect underlying orthogonal performance dimensions [7]. This strategy will be employed using a virtual battlespace to collect data for analysis.

The scenarios, candidate measures and algorithms, and the OTB V2.0 virtual testbed provide a framework for a multi-stage data collection effort within which soldiers with representative background, experience, training, and skill levels will be asked to execute FCS missions as part of a human-MULE robot team. After a verification and validation effort to ensure that the test software produces the intended data products, mission trials will be conducted in which soldiers will team with robots to perform specific assignments within the exercise scenarios. The simulation, instrumented with the selected data extraction and analysis tool, will produce measure data for each of the candidate measures constituting the independent variables.

Dependent variable data will come from a different source. The Objective Force combat development community will be asked to provide subject matter experts to observe the trials and to provide subjective evaluations of the execution of the human-robot team. Accepting the expert judgment to be the reference standard for performance evaluation, the factor analysis process will be employed to examine the value of the component and composite linear factor combinations of the candidate measures in accounting for observed performance. The intent is to seek to identify a reduced set of orthogonal underlying composite measures to which a practically substantial proportion of the measure variance (in relation to expert subject judgment) can be allocated. Conceptually, the process can be thought of as a rotation of the principal variable axes within the data space to identify a new coordinate set that minimizes the data variance. The rotated axes are linear combinations of the original set, and correspond to underlying variable factors suggested by the distribution of the data in the variable space. Factor analysts often look upon this as "first-stage solution" and will typically follow this with further non-orthogonal rotations to achieve what they call a "simple structure". For our purposes however, this will not be advisable, as non-orthogonal rotation has implications to the independence, transformation, and scaling of the data.

8. Experimental Plan

Our planned experimental test program is structured in four parts. Following is a preliminary description of each phase; the detailed test design will be produced during the requirements development effort.

1. Laboratory System Pilot Runs

In the first phase, the test environment will be set up and validated. Pilot runs will confirm that the measurement algorithms are functioning correctly, that the scenario is properly simulated, that the participating virtual platforms and behaviors representations are valid, and that the human operator interface is fully functional. Pilot runs will be conducted to confirm that the design is fully responsive to the requirements of the program.

2. Model Validation and Tuning

The second phase will be devoted to collecting data across the spectrum of operations in the scenario, expert observation and evaluation, and reduction of the measure set through factor analysis. The focus will be on the simplest form of human-robot team, a single operator supervising the activities of one or two robots. The scenario will be executed in the context of FCS embedded individual training with an emphasis on what might become ARTEP/Drill tasks for the human-robot team.

3. Battle Operations in Simulation

We will validate the reduced measure set by applying it to a more complex set of activities representative of FCS battlespace operations. The scenario will involve sequences of the types of tasks that formed the focus for phase two, and it will be executed by a small team consisting of two or more human operators and several virtual robots. This will introduce the dimension of collaboration and allocation of responsibilities to the scenario execution.

4. Field Operation with Live UVs

As an option, we propose in a fourth phase to demonstrate the operation of the performance measurement system in a live

simulated environment using instrumented UVs operating on a tactical range.

9. Conclusions

The key challenge being addressed in this project is the fact that autonomous vehicles, or agents, will need to interact and coordinate with each other and with human systems. Measurement of overall effectiveness in these mixed initiative systems will be essential in order to achieve optimal system performance levels. Behavioral measures of both human and unmanned combat system (UCS) performance obtained in system simulations or in live exercises will be used to continuously diagnose performance and identify required areas of training requirements [3].

Likewise, specialized training will be necessary in order to leverage the complementary cognitive functions of human and machine to forge fighting entities and units with capabilities superior to those of humans or machines in isolation. Embedded training is also projected to be an important part of the Future Combat System (FCS) to assure that performance levels remain high during all operational phases. Overall, a clear and definite need exists for methods and mechanism to assess and determine criteria for successful performance of unmanned systems and manned/unmanned teams in both training environments and the real warfighting situations.

We believe that meeting this need will also lead to significant commercial product opportunities in the large and rapidly expanding military and non-military markets for robotic systems. The focus of our SBIR commercialization strategy will be transformation of the MITPAS prototype into a suite of software modules for use in a variety of mixed initiative and mobile agent applications. The software product will be optimized to meet military and non-military market requirements. It will be sold and/or licensed to DoD and Homeland Defense agencies and prime contractors, to civil organizations that employ remote human controlled robotic agents and unmanned vehicles in hostile environments and for counter terrorism activities and local law enforcement, and also to companies manufacturing and distributing industrial and personal robots. In addition, we plan to explore in Phase the application of the MITPAS as a commercial tool for helping military and non-military emergency response teams determine when and how to use mixed initiative teams on a particular type of mission, e.g., in a bomb disposal situation.

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