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Command, Control, and Communications: Techniques for the Reliable Assessment of Concept Execution (C3TRACE) Modeling Environment: The Tool

by Patricia W. Kilduff, Jennifer C. Swoboda, and B. Diane Barnette

ARL-MR-0617 **June 2005**

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Human Research and Engineering Directorate, ARL

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14. ABSTRACT

The U.S. Army Research Laboratory's Human Research and Engineering Directorate has relied on the use of human performance models to assess the effectiveness of command and control (C2) organizational designs for nearly a decade. This work was based on task network modeling in various versions of MicroSaint (developed by Micro Analysis and Design) as the key methodology. The models have been based on representations of C2 tasks and functions performed by a group of people engaged in various military missions, within conceptual and actual military organizational designs, and using various types of communication and information technologies. These organizations have ranged in size from battalion to brigade level, with the inclusion of message flow from companies to a division staff. This report briefly describes these MicroSaint models and how they led to the development of a modeling environment called command, control, and communications - techniques for the reliable assessment of concept execution (C3TRACE). Thus, models can be rapidly constructed with C3TRACE to analyze multiple organizational, personnel, and systems architectures as they emerge through concept exploration for the Army Future Force.

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1. Objective

The objective of this report is to describe the history of Command, Control, and Communications: Techniques for the Reliable Assessment of Concept Execution (C3TRACE), and the process for developing a model using C3TRACE. C3TRACE provides an environment for targeted evaluation of the effects of different configurations of Soldiers and information technology on performance, that is, both Soldier performance and overall system performance. C3TRACE can be used to identify communication bottlenecks, workload peaks, and decision-making vulnerabilities so that the combined effectiveness of a proposed configuration can be assessed and design changes in the organizational structure or information technology can be recommended. An in-depth report of our first application was published in Plott, Quesada, Kilduff, Swoboda, and Allender (2004). Future enhancements of C3TRACE will also be discussed as well as plans for future applications.

2. Background

The earliest U.S. Army Research Laboratory (ARL) Human Research and Engineering Directorate command and control (C2) human performance models (HPMs) were of a battalion tactical operations center (TOC) operating under current doctrine and using only analog communications and information processing methods (Knapp, Johnson, Barnette, Wojciechowski, Kilduff, Swoboda, & Bird, 1997). This HPM established a baseline for the efficiency and effectiveness of the proposed battalion TOC organizational design. This model was then enhanced to examine the effects of introducing digital equipment that the TOC personnel would use to conduct their missions and communicate among staff cells (Knapp, Johnson, Barnette, Wojciechowski, Kilduff, Swoboda, Bird, & Plott, 1997). Ultimately, these models were modified once more to represent one possible Army After Next configuration where all C2 positions were equipped with fully integrated C2 systems. All restrictions imposed by the limitations of systems in use or development at that time were removed (Knapp et al., 1998). These efforts were eventually brought together in a Computer Modeling of Human Operator System Tasks (CoHOST) project (Middlebrooks et al., 1999). The CoHOST modeling methodology was built and exercised to perform an analysis for comparing different personnel and equipment configurations for operations in today's and tomorrow's Army. CoHOST uses a variety of performance measures to determine effects on decision making.

Recently, ARL developed an HPM for evaluating variations of a concept organization representing the manner in which the U.S. Army would conduct its field artillery missions (Wojciechowski, Knapp, Archer, Wojcik, & Dittman, 2000). The conceptual organization consisted of a Fires and Effects Coordination Cell (FECC) and a field artillery (FA) TOC. This organizational concept was developed by the U.S. Army Depth and Simultaneous Attack Battlelab at Fort Sill, Oklahoma, in order to move toward effects-based fire decisions, centralized fire resources, and opportunities to better accomplish the commander's intent. ARL and Micro Analysis and Design designed an HPM of an FECC and an FA TOC to analyze human performance within those organizational concepts. Individuals performing different tasks and functions on a prototype C2 system in co-located and distributed environments were modeled. This provided an economical means to examine efficiency and effectiveness for the alternate organizational concepts. The FECC and FA TOC models together provided the basis for the development of "sensor-to-shooter" task flow logic. This logic was then incorporated in the FECC and FA TOC hybrid sensor-to-shooter model, also called Performance of the Virtual Soldier (PERVISO), to create a more extensive analysis capability for conceptual brigade-level fires and effects FA organizational designs (Wojciechowski, 2001).

Of particular interest in the analysis of the data output from the sensor-to-shooter HPM was the capability to assess the quality of decisions made by the personnel in the brigade-level organization (Wojciechowski et al., 2000). Decision quality was assumed to be a function of the initial information quality, decay rate, and time since last update. Initial information quality was a measure of the assumed initial quality of each incoming message. The initial information quality can be degraded to reflect actual communication quality or can be left at the default of 100%, meaning that it is "perfect" information. The time since last update determines the information quality, based on the volatility and frequency of change of each element of information. The volatility of the information is defined as how sensitive a piece of information is to change. For example, it is highly unlikely that an enemy mobile unit will remain in a constant place; therefore, it will be assigned a high volatility value. The frequency of change is how often the operator should refresh his or her knowledge of a piece of information. Information that is high frequency and high volatility will have a higher rate of information quality degradation (decay) than low frequency and low volatility information. Information was collected in processing tasks, shared in collaboration tasks, and used in decision-making tasks. Based on the technique just described, a probability that the decision maker would have the information needed to make a good decision was calculated. The output from these models included operator utilization, task drops and interrupts[1], task completions, and sensor-to-shooter timelines. Together, these measures provided investigators with a tool that was used to examine the process of battle command.

The demand for greater flexibility and an easier to use graphical user interface (GUI) of the sensor-to-shooter model led to a redesign of this modeling environment. This redesign resulted in the modeling environment C3TRACE that can be used to develop multiple concept models

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[1]Interrupts are tasks or messages that are temporarily suspended because of a higher priority task or message competing for limited resources.

easily and quickly. C3TRACE provides a point-and-click, Windows[2] standard interface that facilitates the model development process. Its greatest value lies in its capability to analyze many organizational concepts for any number and size of organizations, staffed by any number of people, performing any number of tasks, and under various communication and information loads.

Another modeling tool, IMPRINT (Improved Performance Research Integration Tool) was also developed by ARL. A primary use of this tool is to measure and predict mental workload. It is discussed in detail in Mitchell (2000). C3TRACE is similar to and is often compared to IMPRINT because it has a similar mission-function-task decomposition, as well as the same measure of operator multi-channel workload, visual, auditory, cognitive, psychomotor (VACP) (McCracken & Aldrich, 1984). What distinguishes C3TRACE from IMPRINT is the fact that messages drive the model, and therefore, the workload evaluation is a function of the information load and the associated information management tasks rather than the broader or more general mission operation tasks typically modeled in IMPRINT. C3TRACE tracks the information that is carried with each of these messages. It then uses the current quality of that information at various decision points to determine the probability of making a good decision, based on the available information.

The background provided here is a short overview of the human performance modeling efforts that have taken place within the ARL modeling program. For further details about any of the aforementioned modeling efforts, refer to references provided within this report.

3. Tool Input and Description

C3TRACE includes a user-configurable GUI for easy manipulation of organizations and personnel, the functions and tasks that must be performed, and the communication events that drive the model. The underlying technology is a discrete event simulation engine called Micro Saint Sharp[3]. For a detailed discussion of C3TRACE, refer to the *Software Users' Manual for C3TRACE* (Plott, 2003). The following are three main input categories required to build a C3TRACE model: the organization, the functions and tasks, and the communication events.

3.1 Tool Input

1. Define the organization:

The first step in building a C3TRACE model is defining what level of organizational entities and personnel are to be included in the analysis. In C3TRACE, this is accomplished by the addition

[2]Windows is a trademark of Microsoft.
[3]Micro Saint Sharp is a trademark of Micro Analysis and Design.

of sections and operators into a hierarchical tree diagram. If appropriate, the organization can be broken into sections. For example, an organization could be a Mounted Combat System (MCS) Company Headquarters (Co HQ), the corresponding sections (or vehicles in this example), and personnel within that company. There is no set limit to the number of levels in the organizational hierarchy or the number of operators represented. Figure 1 shows a C3TRACE organization with the necessary operators within each of the three sections or vehicles.

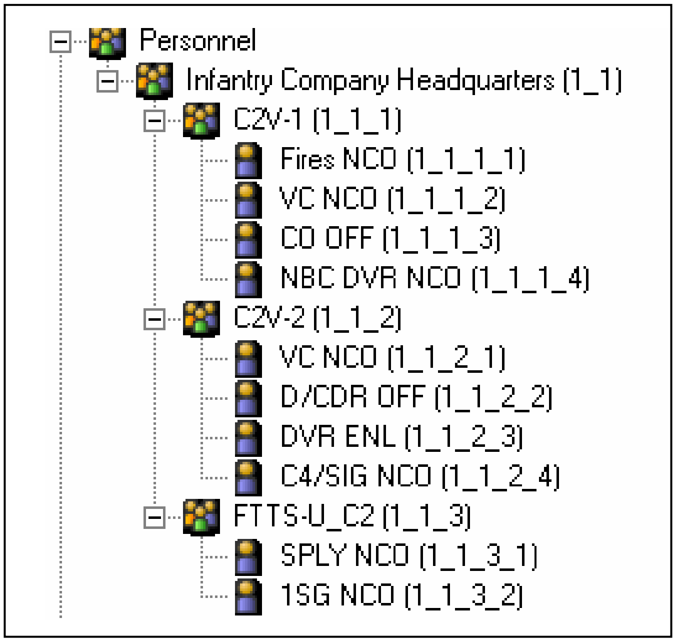


Figure 1. A C3TRACE organization representing an MCS Co HQ.

In addition to defining the organizational structure and personnel allocation, the user can further define the personnel in terms of their specific attributes or personnel characteristics. These attributes include military training level, military rank, length of service, battle command experience, and Military Occupational Specialty. An analyst can also set various model constraints such as the number of simultaneous tasks an operator can perform and the amount of time that a task can be suspended before being dropped permanently.

2. Define the functions and tasks:

The second step needed for a C3TRACE model is to decompose functions into a network of tasks to include sequencing, decisions, and queues. Functions can be defined and sequenced in a flow network just as an operator performs them. All tasks are represented in a task-level diagram. A task-level network diagram window for processing a message is shown in figure 2.

Each task has user-defined attributes including priority; situation awareness (SA) level (perception, comprehension, prediction) (Endsley, 1995); mode (manual, automatic, both); whether decision task, collaborative task, or both; task time information; operator task assignment (primary operator, alternate primary operator, supporting operator(s)); mental workload level (VACP); and decision task information element weighting. Information element weighting is discussed in detail under item 3 which follows. Currently, for decision tasks, the user-defined SA levels are tabulated as frequency counts in the SA output report. In the future, this area will be expanded to include the actual effect of the level of SA on decision making.

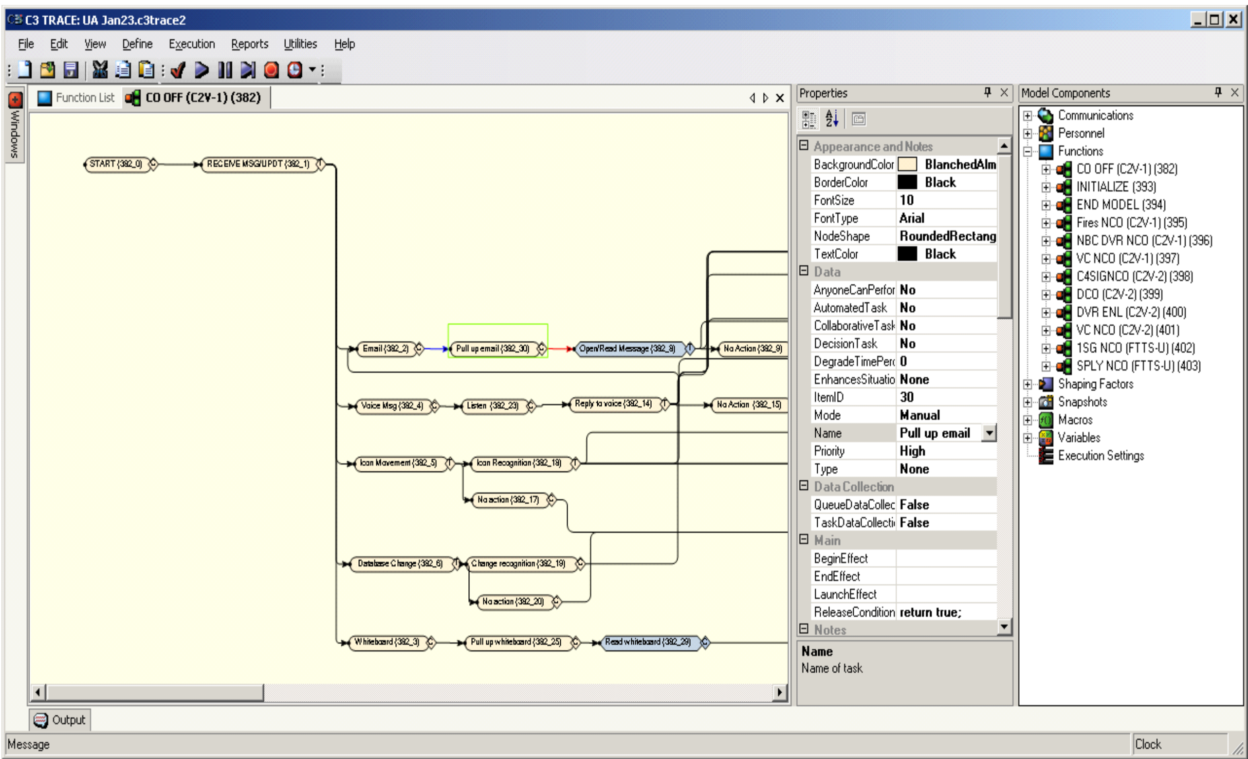


Figure 2. Sample C3TRACE task network diagram and model components.

Decisions (single, multiple, probabilistic, communication-based tactical, user-defined tactical) and queues are included as appropriate to the tasks. A single decision is when there is only one task following the decision task and it does not vary. In a multiple decision, all the tasks following the decision execute simultaneously after execution of the previous task. In a probabilistic decision, a probability will be assigned to each task that follows the decision. During model execution, C3TRACE will determine which one of the tasks will be executed, based on its assigned probability and random number generator. A communication event tactical decision type means that a specific communication event determines the task execution order. A user-defined tactical decision type means that an algebraic expression will determine which task will be executed next.

3. Define the communication events:

The third major category for a C3TRACE model is message traffic including face to face (conversation with another person close to you); digital (common relevant operating picture [CROP] updates, e-mail, “whiteboard” messages, etc.); voice (radio or intercom); and written (a note passed to a certain operator). The communication event information provides the scenario "drivers" for the analysis. The following data are used to describe each communication event: type of communication, time communication entered the input stream, incoming communication frequency, initial information quality, tasks that are triggered as a result of a communication, and communication priority by communication type. Initial information quality is the initial quality of the incoming message and defaults to 100%. It can be changed to reflect known transmission quality of the message or diminished sensor capability. The generated computer simulation model works according to a basic "input-throughput-output" scheme. That is, the input to the model are communication events, which form an information event stream in a frequency-driven time sequence. As these communication events enter the model, tasks are triggered and performed in a pattern that reflects the logic from the task branching and interrupt priorities. Figure 3 shows a segment of a C3TRACE communications list.

Communications

Name	Type	Start Time	Generation ID	Information Quali	Code
41____2_8_FA_will_clos	Voice	12	382_-1	100	InputType[Entity.
57___Redcon_3_	Voice	42	382_-1	100	InputType[Entity.
115___Continue_movem	Voice	127.4	382_-1	100	InputType[Entity.
119___3_92_lead_eleme	Voice	138	382_-1	100	InputType[Entity.
120___SP_now_	Digital	140	382_-1	100	InputType[Entity.
138___CP_2_now_	Digital	165	382_-1	100	InputType[Entity.
148___CP_2_now_	Digital	178	382_-1	100	InputType[Entity.
195___Set_ATK_Griffin_	Voice	226	382_-1	100	InputType[Entity.
221___LD_now___	Digital	250	382_-1	100	InputType[Entity.
257___Have_linked_witł	Voice	312	382_-1	100	InputType[Entity.
259___PL_Rice__traces	Digital	317	382_-1	100	InputType[Entity.
272___PL_Mum__movin	Digital	336	382_-1	100	InputType[Entity.
284___BRT_will_linkup_	Voice	353	382_-1	100	InputType[Entity.
340____3_92_PL_Berry_	Digital	462	382_-1	100	InputType[Entity.

Figure 3. C3TRACE communications list (segment).

In C3TRACE, the user can define the nature of the information that each message carries. This is done with the information elements shown in figure 4, which were taken from the U.S. Army's accelerated decision-making process documentation (Military Intelligence Officer Advanced Course, 1996). The information elements are grouped into six categories: (1) information about enemy force and actions, (2) information about friendly force and actions, (3) feasibility of the current plan, (4) suitability of the current plan, (5) information to judge acceptable risk, and (6) information about the enemy course of action (COA) and potential COAs. Likewise, the user defines the nature of the information required for each decision task. Any or all of the information elements can be weighted to reflect their relative importance to a particular decision. Based on importance, the weighting scale is 1 to 10 in which 1 is the least important and 10 is the most important. Figure 4 shows the information element screen. The modeler must complete an information element screen for each communication event. Therefore, the time needed to complete this set of input will depend on the number of messages in a given scenario. The degree of match between the information elements of the messages and the information required by each decision task is used in the calculation of the decision algorithm described in a later section.

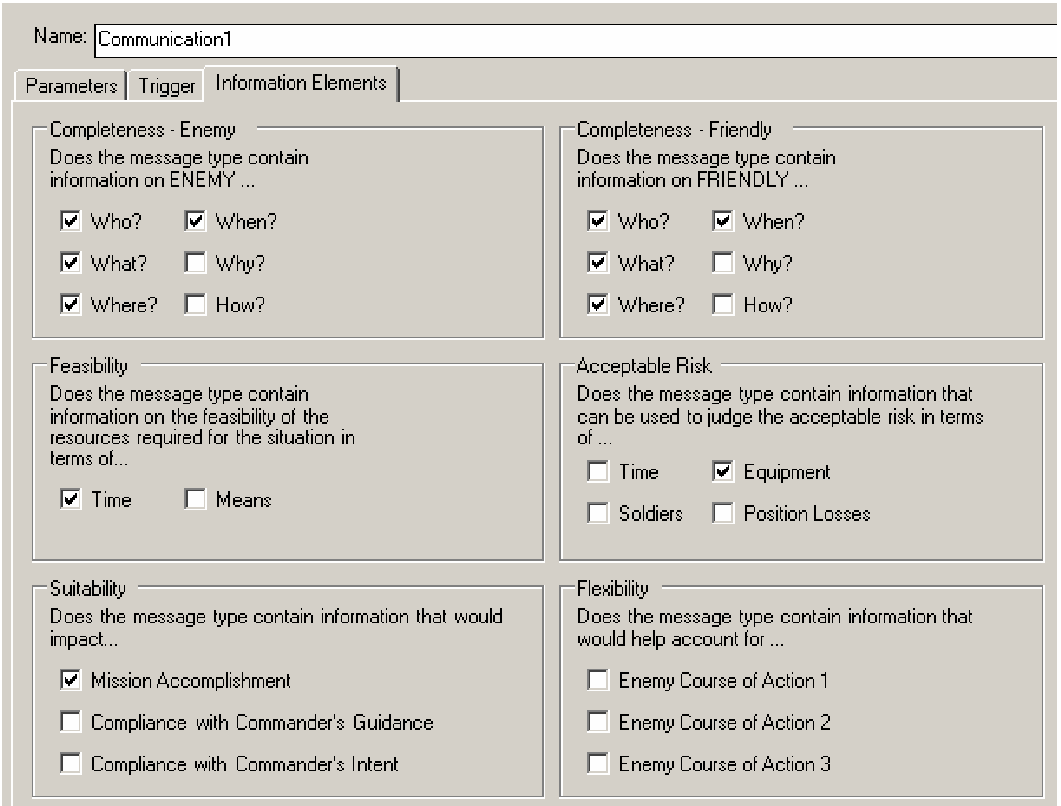


Figure 4. The C3TRACE information element screen.

In addition to defining the organization, functions and tasks, and communication events, the analyst can also define performance shaping factors (PSFs). The factors that can be defined through the PSFs include the personnel characteristics discussed previously in section 3.1, item 1. For each operator, values can be assigned for the attributes that are relevant to the personnel in a particular section. These values will be used to build a logical expression that reflects how the combination of these attributes will affect overall task execution time. A PSF can tell you how an operator with a certain set of attributes will perform a task (take a longer amount of time, the same amount of time, or less time than the mean time). Figure 5 shows the PSF screen.

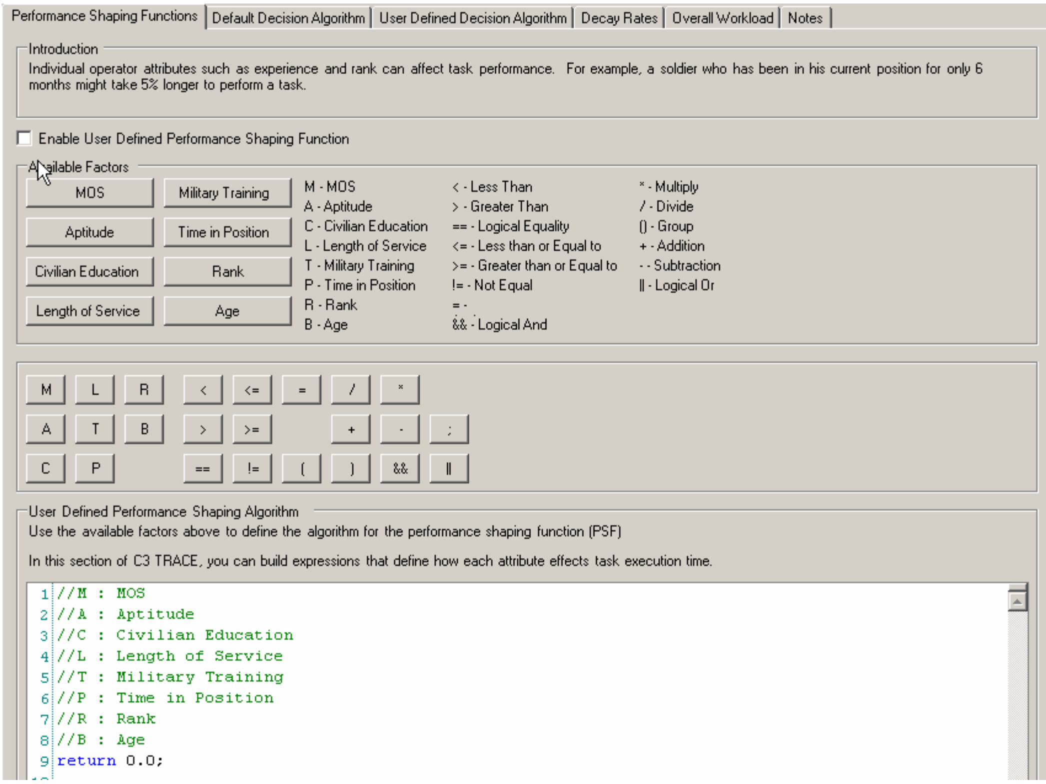


Figure 5. The PSF screen.

3.2 Decision Algorithm Calculation

A successful model of a process will provide predictive measures that can be examined to determine whether the design of the organization or of information flow is correct. In order to establish an accurate assessment of the decisions being made, an "information-driven decision-making" architecture was embedded into C3TRACE (Wojciechowski, Wojcik, Archer, & Dittman, 2001). The basic premise behind this architecture is that information is collected in processing tasks, shared in collaborative tasks, and used in decision-making tasks. This architecture takes into account which operator knows what elements of information, how recent that information is for each operator, and whether the information is sufficient to support the decisions.

The three components of the decision algorithm used in C3TRACE are the initial information quality, decay rate, and time since the last update of that information. The initial information quality defaults to 100% but can be changed, based on the transmission quality of the message or diminished sensor capability. This starting quality level can be adjusted as a function of decay rate and time since last update or when the message is initially executed in the model. As the model executes and messages are generated and forwarded to personnel to be read, the "age" of each information element is computed, based on when the assigned person first read the message and how much time elapsed before the person used the information in a decision task. It is a basic assumption in C3TRACE that the older the information, the less useful it is. It is also assumed that the rate of decay is not the same for all types of information. Information about the location of the enemy is likely to change frequently and rapidly, and thus, that information element will decay quickly. Information about the mission objective of the friendly units is likely to remain stable over a given period of time, however. C3TRACE provides a decay algorithm to capture this differential decay.

A comparison between available information and the information required to make a decision occurs whenever a decision task is executed. Does the decision maker have the right information, processed directly from a message or received from a collaborator, to make a good decision when the time comes? In the end, the "quality" of a decision, that is, the probability of making a good decision, is based on whether the information received by the decision maker satisfies the information required to make a decision, as well as how much the information has decayed over time. Until further data are gathered, it is assumed that any probability over 50% qualifies as a good decision and under 50%, a poor decision. This technique can help to identify system and organizational inefficiencies, bottlenecks, or obstacles relevant to the high quality and current information required for effective decision making.

3.3 Output

C3TRACE produces several standard reports. The operator utilization report displays the total average utilization for each operator (figure 6). This report provides the capability to see which operators are over- or under-utilized.

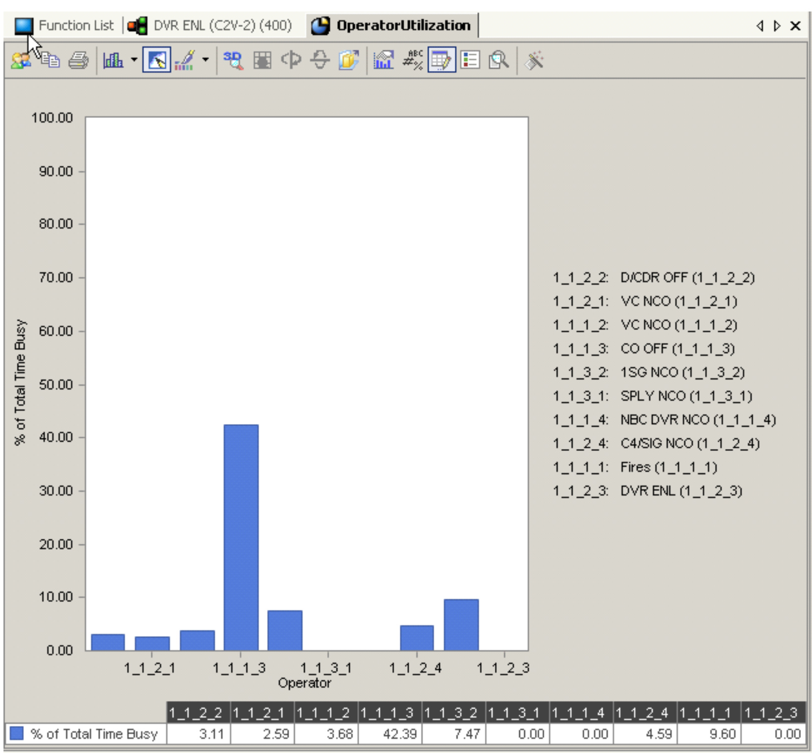
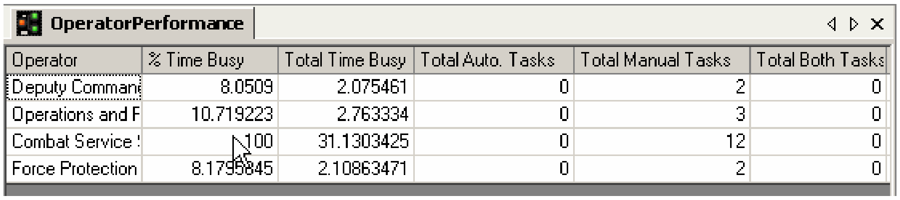


Figure 6. Operator utilization report.

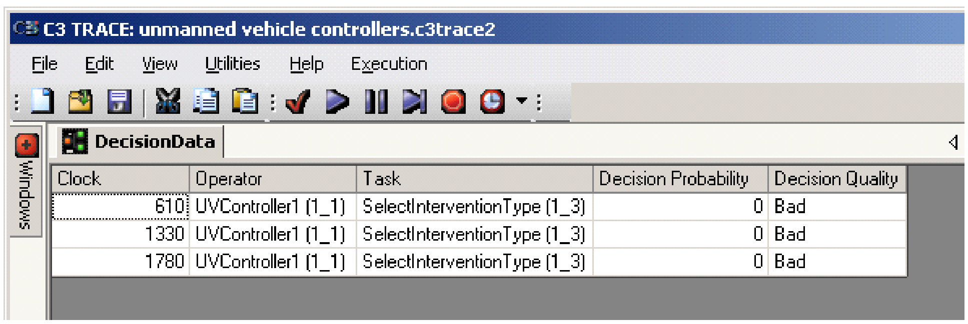
The operator performance report shows various parameters that reflect the overall performance of the operators (figure 7). This report lists the operator name; total numbers of tasks completed, dropped and interrupted; total time busy on tasks; and overall utilization rate.



Operator	% Time Busy	Total Time Busy	Total Auto. Tasks	Total Manual Tasks	Total Both Tasks
Deputy Command	8.0509	2.075461	0	2	0
Operations and F	10.719223	2.763334	0	3	0
Combat Service :	100	31.1303425	0	12	0
Force Protection	8.1795845	2.10863471	0	2	0

Figure 7. Operator performance report.

The decision data report includes function or operator name, decision task name, and decision quality—whether the decision was good or bad (figure 8). This report reflects how well a proposed information network concept, in combination with a given personnel structure, fulfills Future Force requirements for overall SA in support of Soldier decision making.



Clock	Operator	Task	Decision Probability	Decision Quality
610	UVController1 (1_1)	SelectInterventionType (1_3)	0	Bad
1330	UVController1 (1_1)	SelectInterventionType (1_3)	0	Bad
1780	UVController1 (1_1)	SelectInterventionType (1_3)	0	Bad

Figure 8. Decision data report.

The VACP report displays the operator workload data (figure 9). Each operator may be selected and his or her workload is displayed as a line graph for that particular operator. Each resource (VACP) is displayed by a different color line.

Additional reports available are the utilization over time report, sensor-to-shooter report, SA report, interrupted tasks report, and dropped tasks report. These supplemental reports provide additional insight for interpreting analysis results.

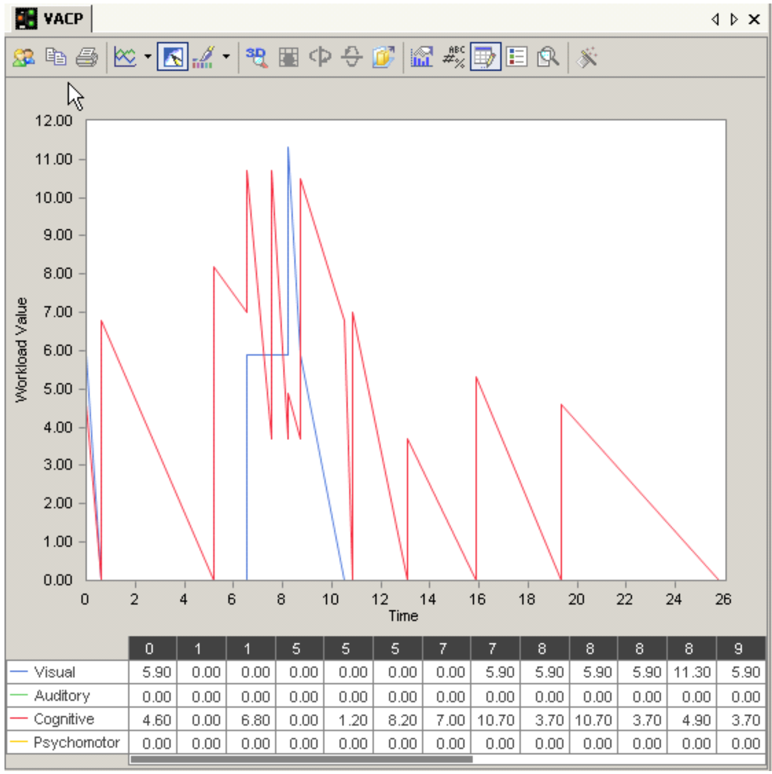


Figure 9. VACP report.

3.4 First Application

In support of the U.S. Army's premier acquisition program, the Future Combat System (FCS), C3TRACE is being used to represent and evaluate performance differences between FCS concepts in baseline and alternate configurations of the unit of action MCS Co HQ. The two configurations were conceptualized to use the same information technology but different personnel configurations and vehicles. Both configurations were obtained from versions of the FCS Operational and Organizational Plan. The baseline configuration was obtained from the October 2002 version (Unit of Action Maneuver Battle Lab [UAMBL], 2002) and the alternate configuration from the June 2003 version (UAMBL, 2003). Results of data from the comparison of these two configurations are discussed in Plott et al. (2004).

4. Future Developments

Future enhancements of the C3TRACE modeling environment include plans to establish a more comprehensive database of PSFs, including the effects of self-efficacy, multi-tasking on mission efficiency and effectiveness, performing tasks and functions while moving, and SA on decision making.

Work is currently in progress to develop an algorithm for self-efficacy (confidence in one's own ability to do well), training level, and uncertainty as determinants of decision-making ability. Plans also include possible linkage to other modeling and simulation tools such as the One Semi-Automated Forces test bed, which is commonly used in concept experimentation (Bowers, 2003), Modeling Architecture for Technology, Research, and Experimentation (Mathis, 2003), and Atomic Components of Thought-Rational (Anderson & Lebiere, 1998). Future applications include the development of a platoon-level model of communication flow to examine the effects on operator performance. Also, there are plans to develop a model to determine the effects of sensor communications on information processing and decision making in a military operations in urban terrain environment.

5. Conclusions

The development of a tool to represent new C3 concepts, with the capability to easily represent any echelon level, the people assigned to that organization, the tasks and functions they will perform, and a communications pattern within and outside the organization, will allow for rapid "what-if" evaluations of numerous concepts without the need for live exercises or experiments. This capability will save time and money and will support the evaluation of many more concepts than could be accomplished by "human-in-the-loop" experiments alone.

It is important to recognize the impact this modeling tool will have on the model-test-model paradigm. After the initial model is developed, it will be beneficial to observe human-in-the-loop experiments (when available) to validate the task networks within the model. When experiments are not available, subject matter experts (SMEs) are another additional source for model validation. With the enhanced data obtained from experimentation or SME input, models can be modified and executed for more realistic and valid results.

C3TRACE is positioned to support analysis of the Soldier-information interface in U.S. Army Future Force concepts. It supports rapid model development for the analysis of the effectiveness of personnel, organizations, and information system technologies in the Soldier-centric, network-enabled battle space.

C3TRACE distribution is controlled by the ARL's Human Research and Engineering Directorate. For more information about the tool or to obtain a copy, contact Jennifer Swoboda, (410) 278-5948, jcrouch@arl.army.mil or Patricia W. Kilduff, (410) 278-5874, pkilduff@arl.army.mil.

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