GENERATING REQUIREMENTS FOR FUTURISTIC HETROGENOUS UNMANNED SYSTEMS

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A cognitive task analysis (CTA) is an effective analysis technique for deriving design requirements for many task domains. However, traditional CTA approaches have limited applicability to futuristic systems because CTA approaches generally require access to subject matter experts, documentation, and previous implementations from which to draw assumptions and expertise. In this paper, we introduce a hybrid CTA framework that allows the generation of information and display requirements for futuristic systems for which no current implementations exist. This analysis technique involves a four-step process including: 1) generating a scenario task overview, 2) generating an event flow diagram, 3) generating situation awareness requirements, and 4) creating decision ladders for critical decisions. We demonstrate the effectiveness of this process through a case study in which functional and interface requirements are generated for the supervisory control of multiple, heterogeneous unmanned vehicles.

INTRODUCTION

A common underlying technique that can be used to analyze a domain in order to derive interface design concepts and requirements is a cognitive task analysis (CTA) (Schraagen, Chipman, & Shalin, 2000). However, one drawback to the use of current CTA approaches is that they are extremely difficult to apply to a futuristic system for which no predecessor exists (Cummings & Guerlain, 2003; Scott et al., 2005). The lack of subject matter experts and documentation, as well as previous implementations from which to draw assumptions and expertise, requires that the CTA approach be amended to account for these additional constraints.

This paper introduces a hybrid CTA framework that takes the analyst from a high level mission goal or a scenario description of a futuristic system to the information requirements and recommendations for an interface design. An example is presented in order to illustrate the process, which culminates in the development of a prototype display that enables a single operator to supervise multiple heterogeneous unmanned vehicles (UUVs and UAVs). For this futuristic multiple UUV/UAV system, there are no operators currently controlling multiple unmanned vehicles either on land or underwater; thus, no SMEs are available to interview.

Through a multi-tiered approach to requirements generation, this hybrid CTA methodology compensates for the lack of subject matter experts (SMEs) and current system implementations. While SME interviews provide feedback to the cognitive task analyst on the expert's interpretation of how the mental tasks are performed (Schraagen, Chipman, & Shalin, 2000), for futuristic systems with no known SMEs, it is difficult to know what lower level tasks need to be performed. Furthermore, existing implementations are traditionally examined to help the analyst understand how low level tasks relate to the overall mission, but in the case of futuristic systems no existing implementations are available for such analyses.

This framework extends previous methods of generating futuristic system requirements (e.g., Scott et al., 2005) by providing a structured process for deriving information and display requirements from the task decomposition phase of a traditional CTA that can be directly applied to the design of a futuristic operator interface.

HYBRID CTA

Our hybrid CTA approach consists of the following components: 1) Generating a scenario task overview, 2) Generating an event flow diagram, 3) Generating situation awareness (SA) requirements, and lastly 4) Creating decision ladders for critical decisions from which we extract information and display requirements. Each of these steps will be described more in detail below. After a basic description of each component, a case study will be detailed that illustrates this hybrid CTA approach.

Generating a Scenario Task Overview

The hybrid CTA approach begins with a mission statement or a scenario description, given to the analyst by an external agency. In the first step of the hybrid CTA, the analyst separates the overall mission into different phases, which are determined by changes in expected operator tasking both in time and sub-task groupings. Within each phase, the phase sub-goals are enumerated and the expected subtasks for each of these sub-goals are detailed. This provides for further subdivision, which allows for the development of a hierarchy that extends from a mission statement down to individual subtasks. Much like a hierarchical task analysis (Annett & Duncan, 1967; Annett, Duncan, Stammers, & Gray, 1971), the task breakdown allows us to analyze the smaller subtasks in order to realize potential failure propagation. Assumptions made during the production of the phase goals and their subtasks should be explicitly stated. If later found to be erroneous, or in need of revision due to process iteration, then the particular phase goal or set of subtasks can be altered accordingly. The scenario task overview provides a foundation on which to base the remainder of the task analysis.

The Event Flow Diagram

The next step involves generating an event flow diagram. While the scenario task overview determines what tasks and subtasks are needed to execute the mission, the event flow diagram demonstrates the temporal constraints, i.e. when the events must occur, particularly in relation to other events. We propose that there are three basic event types in the event flow diagram, which include:

- loops, which represent processes that occur in a potentially iterative fashion until some predetermined event occurs,
- decisions, which require knowledge-based input from the operator, and
- processes, which require some human-computer interaction to support a mission subtask.

Generating SA Requirements

Because situation awareness (SA) is a critical aspect of human supervisory control, particularly time-sensitive command and control operations, the third step involves the generation of SA requirements for each of the mission phases and associated subtasks identified in the first 2 steps. Because SA by definition is inherently linked to temporal constraints, the SA requirements cannot be generated until the event flow diagram is constructed. The SA requirements generated in this step are divided into the three SA levels: Perception, Comprehension, and Projection (Endsley, 1995). For each SA level, the analyst specifies the situation awareness requirements for each of the mission phases and associated subtasks derived in step 1 (Scenario Task Overview), keeping in mind the temporal constraints of step 2.

Generating Decision Ladders

Because decisions in the event flow diagram represent critical events that require detailed understanding of what information and knowledge is needed to support the operator's decision-making process, decision ladders are constructed for each critical decision identified in the event flow diagram. Decision ladders aid in capturing the states of knowledge and information-processing activities necessary to reach a decision (Rasmussen, 1983), and can help identify information that either the automation and/or the human will need to perform or monitor a task. This step involves first developing a traditional decision ladder for each critical decision, as described by Rasmussen et al. (1983). Next, two variations of this decision ladder are constructed: one augmented with corresponding display requirements (DR) for knowledge states and one augmented with possible levels of automation (LOA) where automation could aid the operator. Resultant displays are then designed to meet these display requirements. Designs can then be evaluated by verifying whether or not the requirements are met and hence, whether or not the display supports operator decision making.

As a result of this process, an interface design based on the SA requirements and the decision ladder display requirements will then be traceable to either the SA properties or decisions that led to the requirements in the first place. It is this traceability property that enables the designers to verify the eventual validity of their interface. Moreover, it also allows for analysts and designers the ability to understand the possible impact of changes in an iterative design process.

CASE STUDY

This hybrid CTA was developed in response to the need to generate functional and display requirements for an interface that would allow a single operator to control four unmanned underwater vehicles (UUVs) via a UAV on a shared network. An overall mission statement, generated by a customer, indicated that multiple UUVs would be used to penetrate a harbor entrance to accomplish reconnaissance and surveillance objectives. Two search UUVs would enter the harbor, while another two UUVs would serve as sentries at the harbor exit.

Step 1: Scenario Task Overview

The mission statement was used to develop the scenario task overview, which led to the defining of three primary phases: 1) mission planning, 2) mission execution, and 3) recovery of the vehicles. In the planning phase, the mission plans for the search and sentry UUVs are determined, including their routes, surveillance areas, and communication checkpoints. In addition, the UAV scheduling would occur in the planning phase to ensure communication links between the UUV controllers and the vehicle surfacing schedules. In the execution phase, the UUVs carry out their mission, sending progress reports back via the UAV to the operator, who possibly modifies the mission plans when appropriate. In the recovery phase, the UUVs are recalled or retasked as appropriate. In total, 25 subtasks were identified for all three phases and are detailed elsewhere (Scott & Cummings, 2006).

Step 2: Event Flow Diagram

The event flow diagram (Figure 1, a partial illustration, see Scott & Cummings (2006) for the full report) illustrates for each of the three mission phases, the different subtasks that can be performed within that phase and the possible transitions between them. Although the majority of the subtasks where based on operator inputs, a few were candidates for automation. Alphanumeric labels were given to the blocks so that they could be cross-referenced in the decision ladders and SA requirements matrix.

Step 3: SA Requirements

A SA requirements matrix was then generated with the three SA levels of perception, comprehension, and projection on one axis and the three mission phases on the other axis

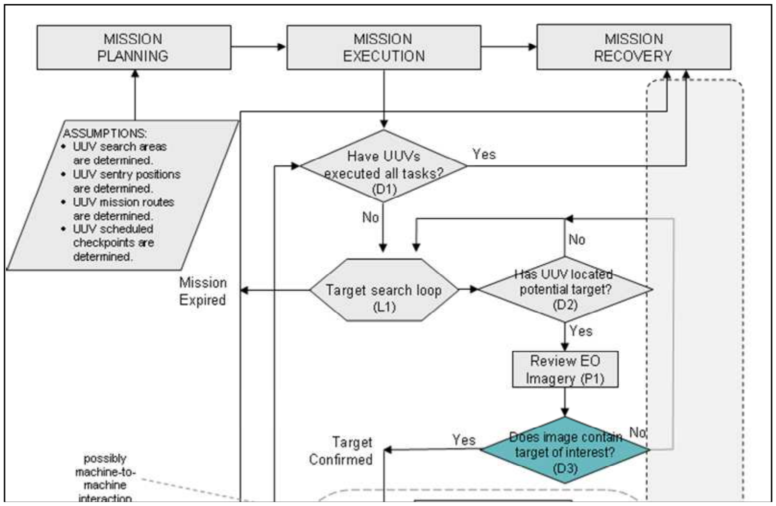


Figure 1. Event Flow Diagram (partial illustration).

	Level I (Perception)	Level II (Comprehension)	Level III (Projection)
	- Visual & audible alert when UAV leaves or returns on-station duty (D2)	- Error/alert message clarification (L1, D2, P1, D3)	- Schedule of estimated UAV on-station availability should be provided on a visual timeline (D2, D3) - Uncertainty of estimated timeframes should be indicated on availability timeline (D2, D3) - Potential missed communications points (D2, D3) - Future likely UUV tracks (D2,
	- All agents' position information (D3) - Hazardous areas (L1, D2) - Geo-spatial boundaries (L1, D2)	- Vehicle limitations (on demand) (P1, D3)	
Acquire Target	- Indicate communications link coverage range when on-station (D2, D3) - Sensor coverage should be	-UUV schedules (D2, D3) -Health & status of UUVs (L1, D2)	

Figure 2. SA Requirements (partial illustration).

(Figure 2; partial illustration, see Scott & Cummings (2006) for the full report). Table 1 summarizes the functional and information requirements resulting from the SA requirements matrix.

Step 4: Decision Ladders

The final step was to generate decision ladders for the three primary critical decisions in the event flow diagram, represented by diamonds in Figure 1; a) does the EO image contain a target of interest, b) is the target moving, and c) are UUVs ready for recall. Figure 3 shows the decision ladder (augmented with the display requirements) generated for decision (a) on the data received from the automatic target recognition (ATR). When the futuristic ATR system on-board a UUV matches an imaged object with a target in its database, the image is sent to the operator along with the suggested match. The operator then has to decide whether the match is valid. Wherever possible in the decision ladder in Figure 3, display requirements are specified that enable the operator to accomplish the knowledge-gathering or information-processing activities required at that step in the decision process. Table 2 summarizes the final set of display requirements that were identified in the ATR decision ladder.

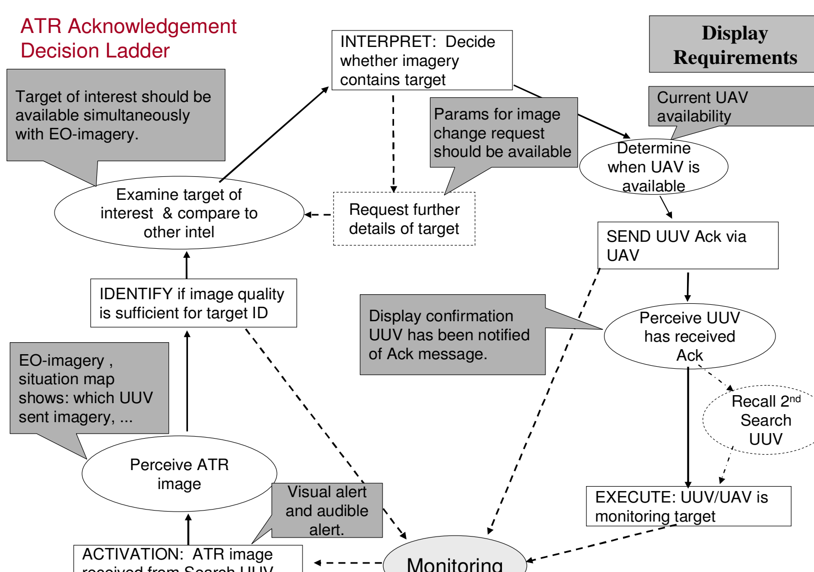


Figure 3. Decision Ladder with display requirements.

Applying the Generated Requirements to a Display Design

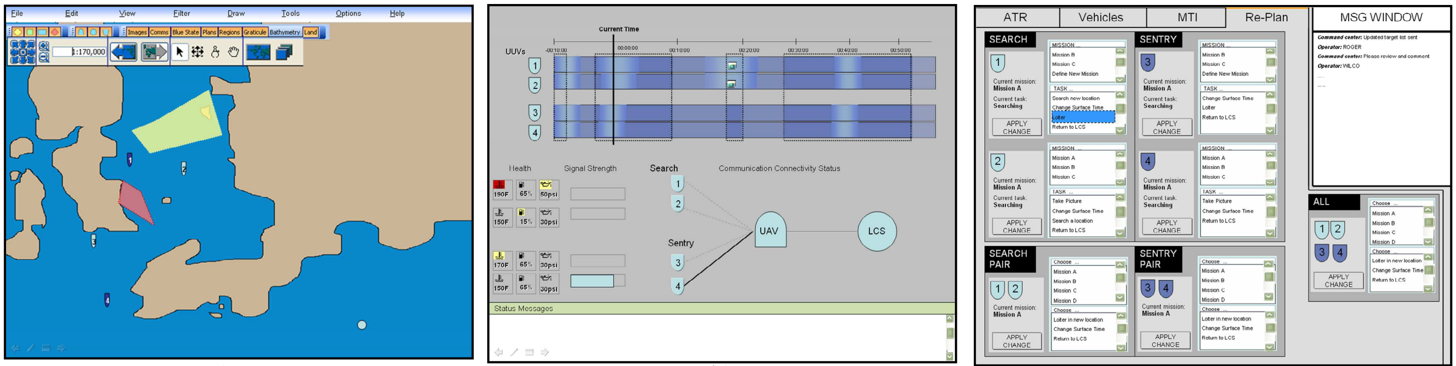
These requirements led to the development of a three-screen display design for the operator interface. The development of the displays involved an iterative procedure with a primary step applying the hybrid CTA generated functional and information requirements, in conjunction with proven user interface design principles (Norman, 1988; Shneiderman, 1998), led to a prototype display design. The resultant three screen interface included a map display, a health and status display, and a multifunctional, tasking display (Figure 4). The map display provides geospatial situational awareness. The health and status display provides scheduling information and vehicle health and connectivity status information for the

Table 1. Functional and information requirements resulting from the SA requirements matrix.

SA Requirements	
Mission Related Requirements	**Vehicle Related Requirements**
Indicate geo-spatial boundaries	Provide visual & audible alert when UAV leaves or returns on-station duty
Indicate Hazardous areas	The strength of comms link to UUV scheduled to check in should be indicated on tactical map
Display UAV moving target indicator (MTI) imagery	Visualize sensor coverage on tactical map
Enable MTI exploration capabilities (playback, zooming)	Provide visual/audio feedback for confirmation of target acquisition
Provide prediction of dropped contact	Indication current health & status of UUVs
Indicate temporal constraints	Display vehicle limitations
Display predicted target track	Indicate UAV handoff constraints
Provide visual & audible alert when target is dropped	Indicate schedule of estimated UAV on-station availability on a visual timeline
All agents' position information	Indicated uncertainty of estimated timeframes and position for handoff on availability timeline
Display potential environmental hazards for tracking	Indicate the UUVs' scheduled checkpoint times on the availability timeline
Display error/alert message clarification	Provide UUV task schedules
Indicate communications link coverage range when on-station	Indicate future UUV tracks
Provide feedback if target is dropped	Display UUV target imagery/sensor data
Display sentry acquisition confirmation	Expected connection should be indicated at UUV scheduled checkpoint time – if UAV out of range / unavailable, missed connection should be indicated
Indicate potential missed communications points	Indicated predicted system health/status
Uncertainty of predicted target location should be displayed on tactical map	

Table 2. Information requirements resulting from the decision ladders.

Decision Ladder Requirements	
Mission Related Requirements	**Vehicle Related Requirements**
Provide visual alert and possible audio alert upon receipt of EO imagery from any UAV or UUV	Indicate current UAV availability and communications link (health and status)
Enable browsing and zooming of EO-image; provide information on UUV that sent image, including position, camera angle & camera range and ATR classification	Indicate UUV information on situation map when EO-imagery received, including UUV position, camera angle & camera range when imagery was captured
Provide intelligence on target of interest simultaneously with EO-imagery for direct comparison	Display most recently confirmed and expected UUV position data and camera focus area, as well as surface schedule
Indicate parameters for EO-imagery change requests (e.g., camera / sensor capabilities)	
Display information related to other possible missions, expected shipping traffic schedule, and current time	
Provide visual alert and audio alert of receipt of MTI data	
Integrate MTI data into situation map: target location, expected heading, time to future positions, and uncertainty of prediction	
Indicate time and position for MTI prediction data on map	



a) b) c)

Figure 4. The three-screen operator interface: a) map display, b) health and status display, & c) tasking display.

UUVs and UAV. Finally, the tasking display provides mission planning/replanning functionality, ATR acknowledgement tasking, as well as other tasking capabilities. In keeping with the systems engineering approach, once designed, we checked the prototype against the requirements.

The traceability provided by the hybrid CTA's structured process enabled us to infer when the display design supported decision-making and situation awareness by verifying that the design met the functional and information requirements. Further verification of this design approach will be done through future user testing on the implemented display designs to evaluate the effectiveness of the provided SA and decision making support.

CONCLUSION

The proposed approach described in this paper provides a framework that addresses the limitations of existing cognitive task analysis approaches for generating requirements for futuristic systems such as an operator station for control of multiple heterogeneous unmanned vehicles. The hybrid CTA framework entails a four-step process that enables the analyst to generate functional and information requirements from a representative scenario description of a futuristic task domain. In particular, this process compensates for the lack of SMEs through the decision ladder generation which helps replicate a potential operator's thought processes. The process also provides the analyst with a clear mapping of any generated requirements backwards and forwards through each phase, should any revisions need to be made. Finally, the case study described in this paper demonstrates how this analysis technique was used to generate functional and information requirements, which was used to inform the design of an interface for controlling multiple, heterogeneous unmanned vehicles.

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REFERENCES

Annett, J., & Duncan, J. K. (1967). Task Analysis and Training Design. *Occupational Psychology, 41*, pp. 211-221.

Annett, J., Duncan, K. D., Stammers, R. B., & Gray, M. J. (1971). *Task Analysis* (Department of Employment Training Information Paper No. 6). London, UK: Her Majesty's Stationary Office (HMSO).

Cummings, M. L., & Guerlain, S. (2003, October 2003). *The Tactical Tomahawk Conundrum: Designing Decision Support Systems for Revolutionary Domains.* Paper presented at the Proceedings of IEEE Systems, Man, and Cybernetics Society Conference, Washington DC.

Endsley, M. R. (1995). Toward a Theory of Situation Awareness in Dynamic Systems. *Human Factors, 37*(1), 32-64.

Norman, D. A. (1988). *The Design of Everyday Things*. New York: Doubleday.

Rasmussen, J. (1983). Skills, Rules, and Knowledge; Signals, Signs, and Symbols, and Other Distractions in Human Performance Models. *IEEE Transactions on Systems, Man, and Cybernetics, SMC-13*(3), 257-266.

Schraagen, J. M., Chipman, S. F., & Shalin, V. L. (Eds.). (2000). *Cognitive Task Analysis*. Mahwah, NJ: Lawrence Erlbaum Associates.

Scott, R., Roth, E. M., Deutsch, S. E., Malchiodi, E., Kazmierczak, T. E., Eggleston, R. G., et al. (2005). Work-Centered Support Systems: A Human-Centered Approach to Intelligent System Design *IEEE Intelligent Systems, March/April*.

Scott, S. D. & Cummings, M. L. (2006). Cognitive Task Analysis for the LCS Operator. Report HAL2006-01, Humans & Automation Lab, Massachusetts Institute of Technology, Cambridge, MA.

Shneiderman, B. (1998). *Designing the User-Interface: Strategies for Effective Human-Computer Interaction* (3rd ed.). Reading, MA: Addison Wesley Longman.