Application of Cognitive Modeling to Tactical Scene Generation

Cory C. Sheffer and Frank C. Vaughan

The Tactical Scene Operator/Associate (TSO/A) Program is an advanced development effort sponsored by the Defense Advanced Research Projects Agency that focuses on reducing operator workload and improving the process of generating and assessing the tactical scene. This combined objective implies the need for some degree of automated decision aids and an effective user interface to those decision aids. To automate such decision aids a model of the user's decision-making process and its associated problem-solving tasks must be constructed. Using cognitive analysis methods, high-level goals of decision makers involved in tactical scene generation and assessment were first identified. Then a cognitive modeling formalism was used to implement a user decision-making model that provides an underlying concept of operations supporting the TSO/A process of tactical scene generation. With this model-based concept of operations, an effective intelligent user interface has been designed. This interface, along with automated processing capabilities, allows the TSO/A operator to rapidly assess the tactical situation and "drill down" to information necessary to support tactical decisions. (Keywords: Cognitive analysis, Cognitive modeling, Intelligent user interface, Tactical scene assessment, Tactical user interface.)

INTRODUCTION

A large number of the combat watch stations on naval tactical units are focused on establishing and maintaining a current and accurate tactical picture for the command. Nowhere is this activity more difficult than on a submarine, where the crew must contend with limited observables from tactical sensors, uncertainty and ambiguity associated with undersea sound propagation, and the tactical complexities of littoral operations. In attempts to improve this picture, new systems with improved sensor processing have been provided to the Fleet. With these advancements in sensor processing and the higher contact densities encountered in littoral operating areas, today's submarine operators are finding themselves inundated with more pieces of information than at any previous time, thus complicating the task of translating this information into actual knowledge about the tactical scene.

In 1994, the Defense Advanced Research Projects Agency's (DARPA's) Ship Systems Automation (SSA) Program began to develop and demonstrate advanced automation capabilities in support of tactical scene generation. Under this program, a top-down evaluation of the functional requirements for tactical scene generation was performed and several associated high-risk technologies were identified, developed, and demonstrated during FY94–97. In September 1997, DARPA's Tactical Technology Office and the Office of the Chief of Naval Operations Submarine Directorate (CNO/N87) initiated a joint program to evaluate the potential of combining these technologies with others under development within the Navy's 6.4 engineering development programs to construct an operational prototype of a Tactical Scene Operator/Associate (TSO/A) suitable for both laboratory and at-sea evaluation.

To develop an effective prototype of an operator's associate that uses automated decision aids and intelligent user interfaces to effect the dual, simultaneously active objectives of reducing workload (and, thus, manning) and improving the overall process, it is first necessary to understand the goals of the decision makers and how those goals fit into the overall operation and control of the ship and its associated systems. Thus, the first step in the SSA Program was to conduct a rigorous, disciplined, top-down functional analysis of manning requirements for both submarine and surface ships. In the resulting SSA concept of operations,[1] watch stations are broken into four major operational groups: Command and Control, Scene Assessment, Tactical Action, and Platform. The Scene Assessment Group is responsible for tactical scene generation. This top-level functional breakdown is shown in Fig. 1, with the Scene Assessment Group highlighted to indicate the location of TSO/A functionality.

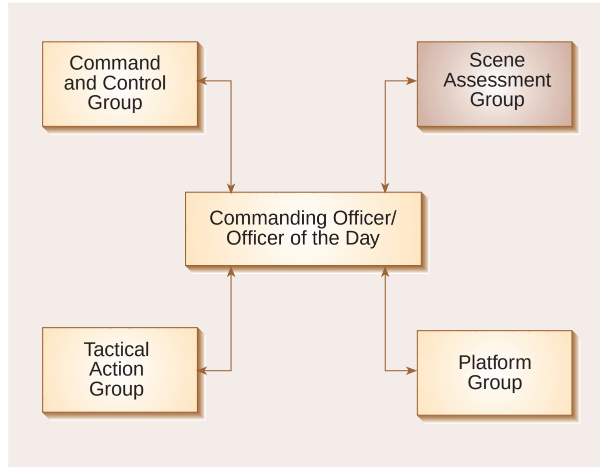

Figure 1. Ship Systems Automation Program concept of operations showing top-level functional breakdown for watch stations.

To take the next step and proceed from this functional breakdown to implementing actual automated decision aids and user interfaces requires having some type of model of the operator's decision-making process and the associated set of problem-solving tasks used to effect the various functions required to generate and validate the tactical scene. The approach we have taken in developing such a model for the TSO/A is that of cognitive task analysis and cognitive modeling. As described in Ref. 2, cognitive modeling of this type is a fundamental aspect of cognitive engineering, and, when combined with cognitive task analysis, it provides an effective basis for understanding the requirements of military decision-making tasks in particular. Coury and Strauss,[2] while pointing out that the use of such techniques has a well-established basis and is the core activity of many cognitive engineering efforts,[3] also discuss some of the research and development issues faced in applying the formalism and techniques to real military decision-making tasks and describe how current theory and research are helping to guide our efforts at APL.

Figure 2 depicts the application of this process to two aspects of TSO/A: development of a concept of operations for TSO/A that comprises a relatively detailed set of hierarchical user goals and tasks, and application of this concept of operations to develop and then evaluate candidate user interfaces. As shown in Fig. 2, this formalism represents the human cognition process as starting with a set of high-level goals that can then be successively decomposed into a hierarchical network of tasks. This hierarchical decomposition process uses what is referred to in the cognitive science and engineering literature as a GOMS-based approach, i.e., goals/operations/methods/selection. That is, starting with a set of high-level goals, one decomposes those goals into lower and lower levels by specifying methods for achieving goals as sets of operations specific to the application domain of interest. The models developed using this GOMS-based formalism can then be implemented computationally and used in simulations of human/system interaction to predict and assess performance. This is the manner in which the TSO/A concept of operations model can be used to develop intelligent or smart user interfaces and then evaluate such candidate interfaces before actually implementing them in operational systems.

In a separate but closely related Office of Naval Research program, we have constructed cognitive models of subsets of the TSO/A scene assessment problem-solving tasks using the COGNET framework.[3] COGNET (COGnition as a NEtwork of Tasks) is a set of tools for performing cognitive task analysis and building models of human interaction with complex environments.[4] Using these models of TSO/A operator/display interaction, we have obtained

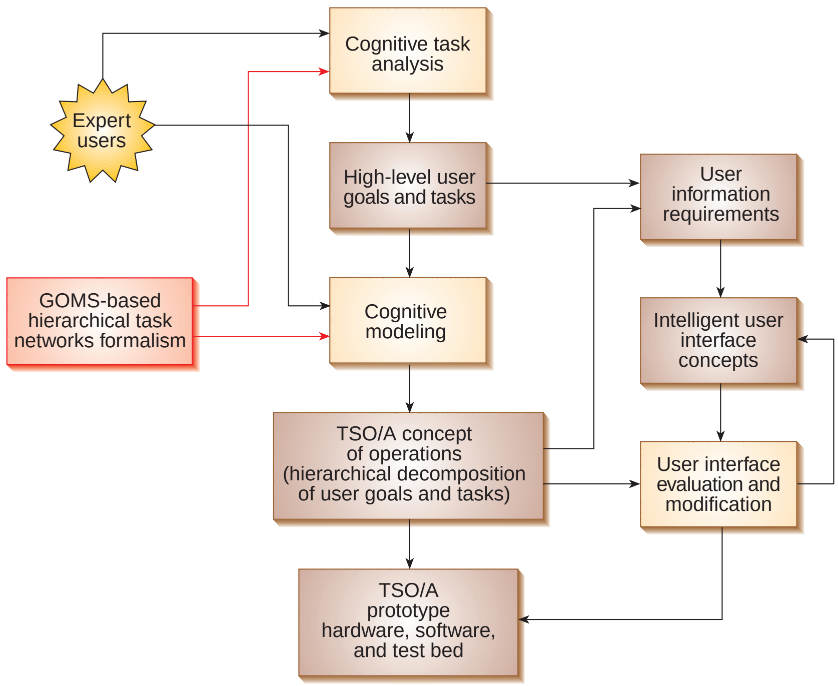

Figure 2. Application of cognitive task analysis and cognitive modeling in developing the Tactical Scene Operator/Associate (TSO/A) concept of operations and intelligent user interfaces. (GOMS = goals/operations/methods/selection.)

quantitative measures of operator performance differences as a function of different display formats.

TSO/A HIGH-LEVEL GOALS

The ultimate validity and effectiveness of the TSO/A prototype/test bed derived in the manner depicted in Fig. 2 depends extensively on the validity and accuracy of the process used to derive the high-level user goals and tasks attributed to the tactical decision maker/scene assessment officer. That is, it is fundamentally important to first understand the basic goals of the decision makers involved in tactical scene generation and to make an assessment in the context of how the TSO/A prototype/test bed will ultimately be implemented in a GOMS-like hierarchical task framework. To accomplish this, investigators familiar with the GOMS-based hierarchical task decomposition formalism carried out an extensive and iterative process of cognitive task analysis involving interviews of experts in submarine tactical scene generation and assessment. This process led to the identification of three major high-level goals:

1. Acquire and maintain **situational awareness** (i.e., understanding the world around you)
2. Maintain ability for rapid **situation response** to triggering events, operating constraints, etc.
3. **Manage uncertainty** (e.g., correct system solutions, make high-level decisions, and manage incomplete, imprecise, and ambiguous information)

Then, as shown in Fig. 2, each of these high-level goals is hierarchically decomposed into a set of successively lower-level user goals and associated problem-solving tasks that, together, comprise the TSO/A concept of operations.

TSO/A CONCEPT OF OPERATIONS

The TSO/A concept of operations is developed from a methodical and successively hierarchical decomposition of the three high-level goals identified in the cognitive task analysis process. As shown in Fig. 2, this process consists of continued in-depth interviews of experts in submarine tactical scene generation, assessment, and then formulation of the resulting set of associated problem-solving tasks in the GOMS-based formalism.

Situational Awareness

In establishing situational awareness, three areas are considered: ownship, tactical situational context, and contacts. To understand how ownship fits into the tactical situation, some basic information is necessary: position, course, speed, and depth. Other information on ship status affects how ownship can influence the environment. This includes data on acoustic health; ownship signature; sensor, propulsion, and housekeeping status; operating constraints; acoustic limitations; and the scheduling of ownship evolutions.

Tactical situational context can be defined as the physical and political world that exists around us. The physical world can be defined as geography, bathymetry, corridors, and environmental factors (e.g., weather, sound velocity profile, biologics). The political world can be defined by such factors as geopolitical boundaries, order of battle, force capabilities, and coverages. In most cases, these elements are fixed and the information can be provided by various databases. Some, like the environmental factors, are constantly changing and will need to be reevaluated regularly.

The final area of situational awareness is the understanding of the contact situation. This is where the majority of the operator's focus will be. In trying to understand the contact situation, operators ask themselves five basic questions:

- Where is everybody? Position (range, bearing)
- Who are they? Identity
- Where are they going? Velocity (heading, speed)

- What are they doing? Behavior (maneuvers, events)
- What do I expect them to do? Intent (anticipated events, activities)

The answers to these questions, along with the uncertainty associated with those answers, are the focus of TSO/A processing. This information will draw the user's attention to particular contacts based on how they affect him and the confidence he has in the data.

Situation Response

Situation response deals with answering the question, "How do these contacts affect me?" After, or in the process of, attaining situational awareness, an operator's attention is directed to particular contacts by a couple of different mechanisms. One aspect is how things affect him. Contacts can pose obstacles to ownship's intentions in the following ways: collision, defense of ownship, stealth, maintaining situational awareness, and controlling mission.

Avoiding collision is a safety issue and will almost always be an operator's top concern. Some of the factors necessary to drawing the operator's attention in this area are range, closest point of approach, and bearing rate: all indications of a contact's proximity to ownship. The operator's attention in the defense of ownship is directed by information such as the identification of a hostile contact or a torpedo in the water. Maintaining stealth is determined by the probability of counterdetection of ownship by a given contact. Maintaining situational awareness deals with the need to keep track of a contact. If a contact is lost or is about to be lost, an operator's attention may be drawn to that contact in order to maneuver ownship such that sensor coverage is maintained. The final operator concern is controlling mission. This goal obviously depends on the context of the mission being performed. It could be a wartime mission where engagement is the top priority and attention is focused based on that priority, or it could be an intelligence-gathering mission where there is a prioritized list of contacts or events that will guide the operator's attention.

Manage Uncertainty

Managing uncertainty entails managing the incomplete, imprecise, and ambiguous information that one is presented when trying to generate a fused scene from multiple sources that often provide conflicting information. Uncertainty and ambiguity of contact information are found in three general areas: range, bearing, course, and speed; classification; and association.

Whether an operator's attention is focused on a contact in terms of its effect on him or just by the amount of uncertainty associated with it, an operator must understand the uncertainty associated with the contact in these three areas. The first (range, bearing, course, and speed) involves such information as whether there are any ranging measurements or estimates associated with the contact, whether bearing ambiguity has been resolved, etc. The second area (classification) involves whether any observed or inferred operational behavior traits exist that could be used to indicate whether the contact is a merchant or is neutral, friendly, or hostile, for example. If there are observed and inferred classifications, do they agree with each other? The third area (association) is a result of multiple pieces of information being fused into a single contact. Each contact can have multiple associated hypotheses, depending on how the information is put together. All of these areas must be managed so that the limits of the picture being created are understood.

INTELLIGENT USER INTERFACE

Once the high-level goals are identified and then successively decomposed into lower-level goals and associated problem-solving tasks that together comprise the TSO/A concept of operations, the next step is to design the user interface (Fig. 2). Two major objectives are identified for the design: (1) to allow the operators to accomplish their three identified goals for tactical scene generation, and (2) to make the design simple to operate and thereby maintain the focus on reduced operator workload.

To make a user interface simple with the relatively large number of subsystems involved, two goals need to be accomplished in the design. First, the design must minimize the operator's knowledge of individual system manipulation. Second, the design needs to allow the operator to focus on the information space as opposed to focusing on the individual systems that provide the separate information components. To accomplish each of these objectives with a reduced manning contingent requires an intelligent user interface that needs to automatically address some of the problem-solving tasks that would otherwise be allocated to sensor system operators. As shown in Fig. 2, cognitive task analysis and modeling are used to incorporate the appropriate problem-solving tasks in the user interface and then, by exercising the interfaces within the overall TSO/A concept of operations, to evaluate resulting candidate interfaces.

SUPPORTING THE OPERATOR'S GOALS

The TSO/A workstation uses three displays arranged as shown in Fig. 3, allowing operators to focus on any one screen while still being able to monitor the other two screens through their peripheral vision. The center display and the left-most portion of the right-hand display make up the TSO/A common display. The common display almost never changes, and it supports the operator's first two goals: situational awareness and situation response.

Situational awareness is provided to the operator in two ways. The first, a geographical picture, is common to all of the operators involved in scene generation. The second, a contact evaluation plot, represents all of the contacts in the scene in a time-bearing format that can be more useful at times for bearings-only contacts. A contact read-out area also exists, which provides textual information on hooked contacts.

The second goal, situation response, is supported by the alert management display (Fig. 3), which is used to focus the operator's attention on tracks that are deemed important. The alerts are grouped into the five categories mentioned in the situation response section (collision, defense of ownship, etc.) along with three categories dealing with uncertainty—kinematics, classification, and association. The order of the tracks constitutes the track's importance to the operator. The ranking is determined either by an automatic ranking algorithm or by a ranking scheme set up by the operator.

The left-hand display and the main portion of the right-hand display of Fig. 3 support the operator's third goal, managing uncertainty. In order to manage uncertainty, the operator must be able to investigate the different aspects of the contact starting with the track's determined solution, through all of the various information processing systems, down to the raw data from the various sensors. The right-hand display is dedicated to the information processing involved in determining the main components of the track's solution. Those components are the track's kinematics, classification, and association and ownship's vulnerability to that track. The left-hand display is dedicated to the various sensor systems providing the raw data.

SIMPLIFYING USER INTERACTIONS

Numerous systems are required to provide operators with the information they need to accomplish their desired goals in generating and assessing the tactical scene. So many systems are essential that the knowledge necessary to operate each individual system would call for a "super-operator" with a tremendous amount of knowledge about each individual system. Since the amount of training and time entailed to develop this

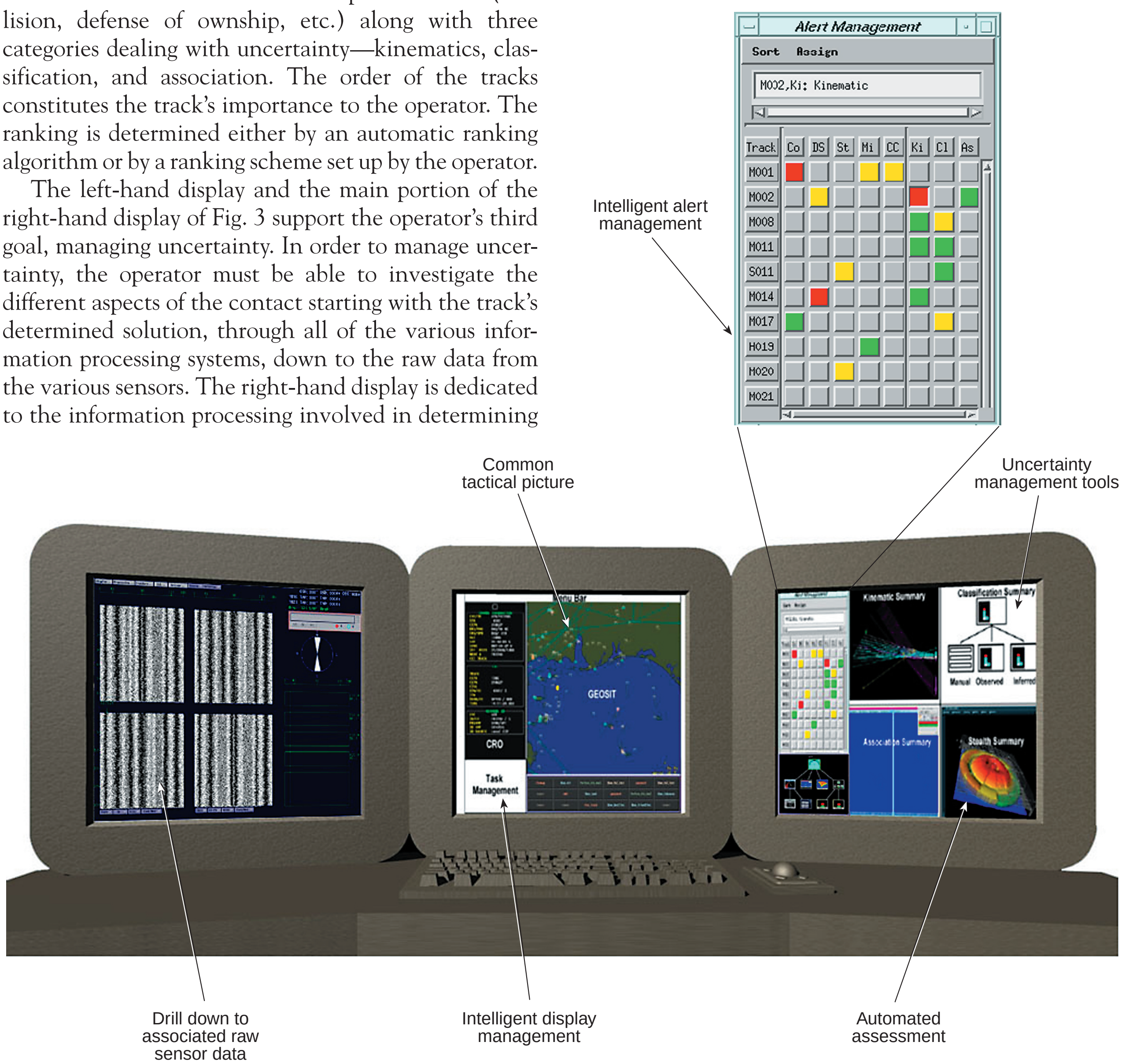

Figure 3. TSO/A user interface design.

super-operator is completely unreasonable, the user interface design must be simplified to allow operators to concentrate more on the information being presented to them rather than the manipulation of the systems to view the information they want. To help accomplish this, TSO/A is using a system that was developed under the SSA Program by Orincon Corporation: the Tactical Assistant for Interaction Planning and Execution (TAIPE). TAIPE functionality includes

- Attention directing
- Interaction planning
- Subsystem interfacing
- User interface management
- Local task management
- Workload consultation
- Global task management

These capabilities allow interaction plans to be developed to help accomplish specific goals with regard to scene generation and assessment. Goals are posted when an operator acknowledges an alert or group of alerts for a given track. Once a goal is posted, an interaction plan is initiated. The interaction plan then brings up the necessary information for the operator to make a decision about the particular alert that he acknowledged. Interaction plans are created ahead of time by subject matter experts, allowing operators with little knowledge of the individual systems to make decisions on the information presented to them. Operators are able, however, to create new interaction plans and to modify existing plans as necessary to better serve their individual needs.

A set of interaction plans has been created for the TSO/A system.[5] One of these plans is graphically depicted in Fig. 4 and is provided as an example of how an interaction plan would execute. This interaction plan would execute based on a goal posted by a possible collision alert. Multiple actions would initially occur automatically to configure the three displays for collision track analysis (Fig. 5). The following actions would occur on the center, or common, display: hook track on collision course, display range rings, display uncertainty ellipse, zoom display to a range that includes both the hooked track and ownship, and display the closest point of approach window. On the left-hand panels of Fig. 5, the sonar display would be reconfigured to display the beams containing the contact of interest. On the right, the kinematic analysis display would be brought up for the track of

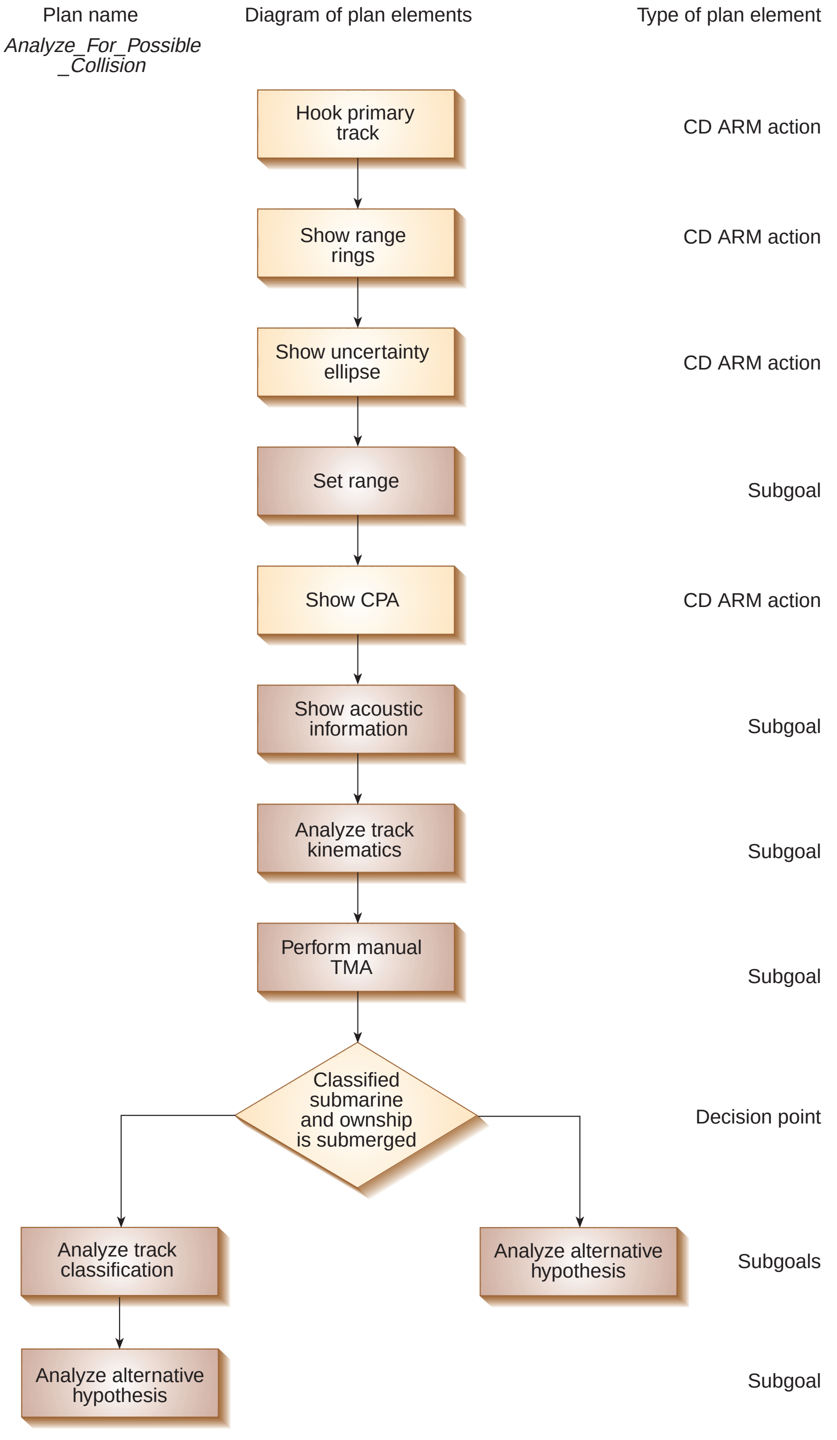

Figure 4. Graphical representation of a possible collision interaction plan. (CD ARM = Command Display Auto Remote Manipulator; CPA = closest point of approach; TMA = target motion analysis.)

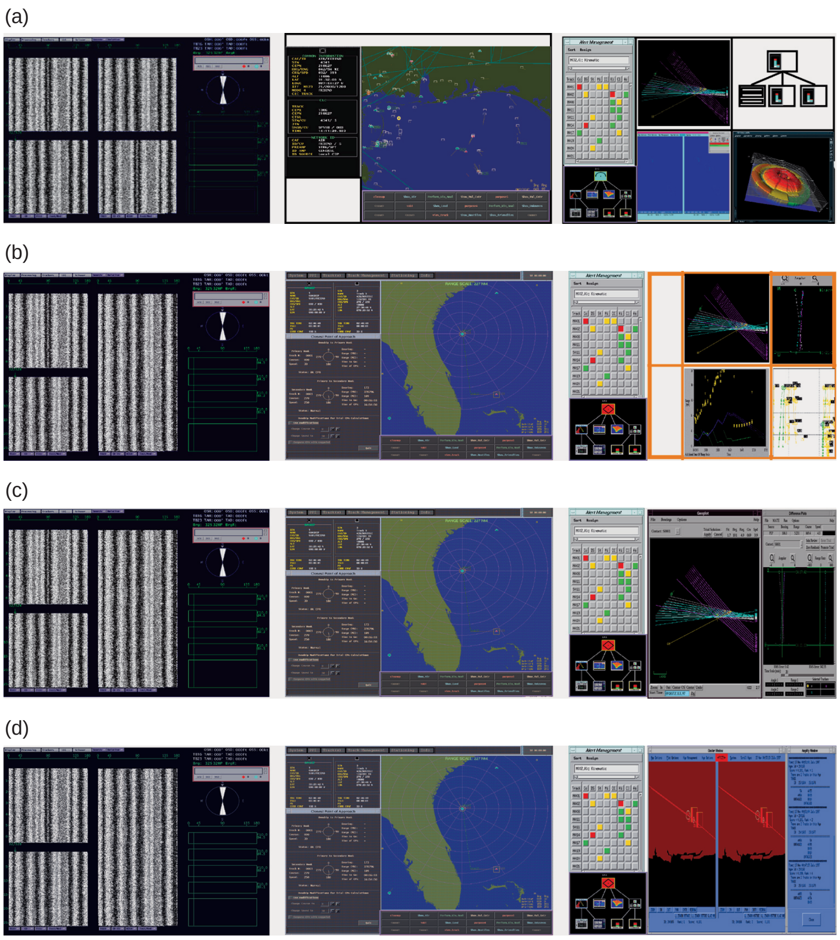

Figure 5. The illustrated sequence portrays the changes in the TSO/A displays as a result of the collision interaction plan: (a) initial display configuration, (b) configuration after the plan is initiated, (c) configuration after the next step, and (d) configuration after the final step.

interest. All of these actions would occur automatically just by the operator's acknowledging the alert.

Follow-on actions occur only as the operators step through them. The process is set up this way for a couple of reasons. First, it prevents information from being missed as a result of being automatically stepped through at too fast a pace for the operators to comprehend. Second, it allows the operators to perform other more detailed actions within a step if they deem it necessary to better understand the information being presented. However, the person developing the interaction plans must be careful not to make the interactions too general, thus requiring the operator to make additional detailed actions to clarify the picture. If the interactions are too general, the operator's understanding of the individual systems would still have to be quite high, thus still requiring a super-operator's understanding and knowledge to operate the system.

In the example shown in Fig. 4, the follow-on actions affect only the right-hand display in Fig. 5. The initial action would cause a stepping through of the individual automatic solutions for the given track. This is included as part of the subgoal *Analyze track kinematics*. This allows the operator to evaluate all of the solutions that have been developed for the track for consistency and accuracy. The operator's next action would bring up the manual target motion analysis display, allowing him to determine a manual solution if he so desires. If he does not, he initiates the next action, which involves a decision point.

If the submarine is deep (i.e., submerged deeper than periscope depth), only another submarine poses a collision threat, so the operator would want to investigate the accuracy of the classification of the track. This would cause the *Analyze track classification* subgoal to be initiated. If the submarine were at periscope depth or on the surface, multiple classes of tracks would pose a collision hazard, and the need to determine the type of track that poses a collision hazard would go away. In this case, the *Analyze track classification* subgoal would be completely bypassed and the next step would be initiated instead.

This final step would initiate the *Analyze alternative hypothesis* subgoal. This allows the operator to determine if there is an alternative hypothesis (i.e., the way measurements are associated with each other) that is more believable than the propagated one. For example, instead of one track on a collision course, another hypothesis could have two different tracks from the given measurements. If so, the operator could determine if the collision hazard remained a concern under this hypothesis.

Interaction plans are an aid to the operators. They do not remove operators from being able to control the system or make decisions for themselves. Operators can abort an interaction plan at any point they wish. They are not trapped into an interaction plan every time they initiate one. An operator can also acknowledge alerts for another contact while currently in an executing interaction plan. This will cause a new interaction plan to be initiated based on the goal posted by the current track. The preempted interaction plan can then be resumed from the start of the plan if the operator desires.

Another way TSO/A simplifies the user interface for operators is by presenting information based on an information space point of view rather than a system space point of view. Operators think about a contact based on its various components (i.e., kinematics, classification, and association) since it is those aspects that are most directly linked to information or knowledge that they need to achieve their three high-level goals. They do not think about the track or contact based on the individual systems involved. In fact, individual systems can provide information related to multiple components of each contact or track. So TSO/A automatically collects information provided by the various systems and organizes or categorizes it in terms of the components of the contact or track that the operators are most directly concerned with. This makes the individual systems basically invisible to the operators. All they see is the TSO/A system as a whole.

To help operators navigate and understand this information space, TSO/A has provided them with a couple of tools. The first tool is a track-hooking concept. The idea is to have all related information concerning a track hooked at the same time the track is hooked on the primary display. This approach instantly provides operators with focused information about the track of interest, no matter where they are in the information space. When the primary hook on the geographic display hooks a track or a track is hooked on the alert management display, the four summary panels on the right-hand display in Fig. 5 are updated with information based on the hooked track. The sonar display also reconfigures to display sonar information concerning the hooked track. This reconfiguration provides operators with summarized information on each of the track's components just by hooking the track. Along the same lines, any screen that is brought up by operators will have information concerning the hooked track displayed without their having to do any other manipulations. The primary hook provides a top-to-bottom link of all the information related to a contact. In a similar manner, operators should be able to have low-level information linked back to the contact it relates to. In TSO/A, if operators hook a piece of information in a lower-level display not related to the currently hooked contact, a secondary hook on the geographic display will hook the associated contact. This secondary hook will affect only the geographic display.

The second tool to help operators keep track of where they are in the information space is an information space navigation display (Fig. 6). This display is in the form of a tree structure with the top node being the primary hooked contact. The four branches extending from the contact are based on the components of the track: kinematics, classification, association, and vulnerability. The icons attached to the branches represent the particular portions of the various systems that support that part of the information space arranged in a hierarchical order. As operators navigate through the various systems either manually or by an interaction plan, the information space navigator keeps them informed as to where they are located in the information space. It does this by highlighting the appropriate icon for the current areas that are being displayed. If operators wish to maneuver through the information space for a particular contact manually, the navigator allows them to click on the icon corresponding to that component of supporting information they are interested in. The information space navigator, in turn, brings up the associated display.

CONCLUSION

As a result of the environment they have to work in, submarine operators have always wanted and needed the means to overcome the paucity of high-quality information required to generate a more complete and clearer tactical picture. Navy laboratories, academia, industry, and Fleet staffs, themselves, have responded by developing more and better organic

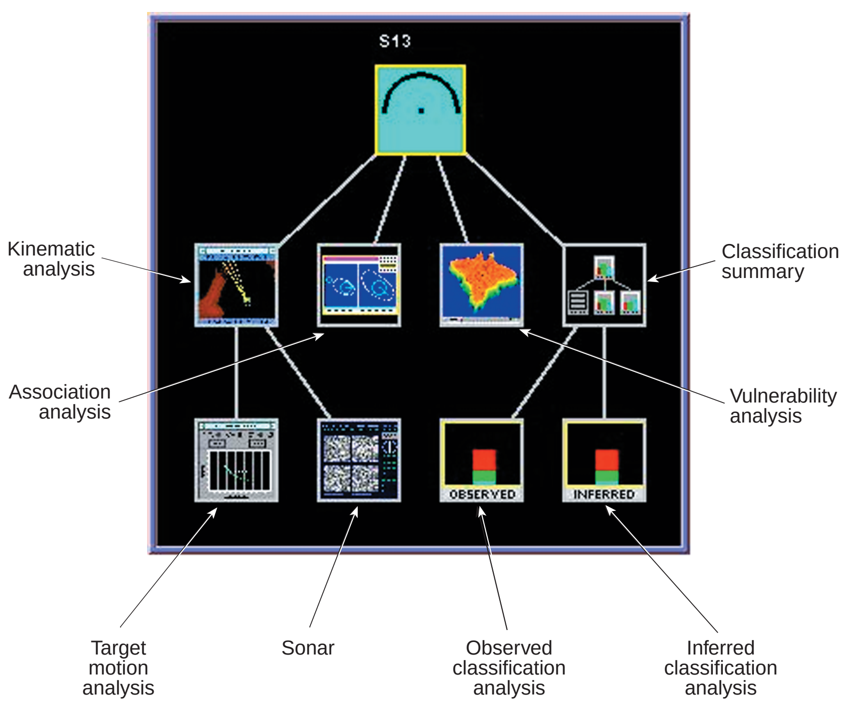

Figure 6. TSO/A information navigation display.

sensor systems as well as providing enhanced connectivity to offboard, inorganic sources of tactical information. However, without additional operators to manage this increased availability of essentially raw information and translate it into useful, reliable knowledge of the local, *in situ* tactical scene, quite a few systems and tools on today's submarines are ignored just because there are not enough people to use all of them. TSO/A is an attempt to bring together all of this information and to apply advanced automated decision aids coupled with intelligent user interfaces to reduce operator workloads while simultaneously improving the overall process of generating and assessing the tactical scene.

We have applied ongoing research in the area of cognitive engineering and modeling to develop a TSO/A prototype test bed suitable for both laboratory and at-sea evaluation by Fleet operators. By looking at the problem from the operator's point of view, using cognitive task analysis to identify his high-level goals, and then using a cognitive modeling formalism to hierarchically decompose those goals into lower-level goals and associated problem-solving tasks, it has been possible to design a system that focuses all of this information in such a way as to support the operator in achieving his goals.

This design requires more than just focusing the information, however. To prevent creating a system requiring a super-operator, tools must exist that allow the operator to thoroughly investigate all of the information concerning a contact without detailed knowledge of each system involved. We have used a cognitive model of the basic TSO/A concept of operations to both design and help evaluate intelligent user interfaces that make the underlying sensor systems invisible to the operators and support them in maintaining a decision and information space–centered focus.

TSO/A will be evaluated in FY99 to determine if this design improves the submarine operator's ability to generate and assess the tactical scene. It will be assessed on its ability to accurately generate the tactical scene and also its effectiveness in allowing operators to handle the amount of contacts and information being presented them today and in the future.

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