Supporting Dynamic Contextual Decisions in Supervisory Control of Heterogeneous Unmanned Vehicles

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Abstract— **In the control of heterogeneous unmanned vehicles in future military operations, it will be critical to provide goal-based decision support for human operators. The incongruent limitations and capabilities of heterogeneous vehicles contribute to the cognitive complexity of supervisory control, particularly under time critical constraints. Furthermore, there are additional challenges to effective decision making in these multiple vehicle command and control environments, including understanding the currently available options, information uncertainty, and interruptions arising both from the system and/or the surrounding environment. To address these challenges, we developed an interactive decision aid, called the dynamic contextual decision tree (DCDT), which assists decision making in supervisory control of multiple heterogeneous unmanned vehicles (UVs). The DCDT was applied to several decision making processes involving a mix of unmanned underwater and aerial vehicles, which included the automatic target recognition acknowledgement process.**

Index Terms—**multiple unmanned vehicles, supervisory control, heterogeneous vehicles, dynamic decisions, automated target recognition.**

I. Introduction

As automation is introduced to handle low-level decision making in the unmanned vehicle operation, the human operator's responsibility becomes more of supervisory control as opposed to manual control. This in turn shifts the human responsibility to making decisions at the mission management, goal-based level instead of lower level control decisions such as heading, altitude, attitude, etc.

Supervisory control of unmanned vehicles is an embedded control problem, as depicted in Figure 1. Moving from the right most inner loop to the outer most loop on the left, we move from control tasks that are based purely on physical laws to control tasks that require judgment-based experience as well as abstract reasoning. Although control loops based on physical constraints such as lift, weight, thrust, and drag are suitable for higher levels of automation such as autopilot, control loops that require knowledge based reasoning cannot always be automated with today's technology.

However, decisions based on reasoning and judgment are the most difficult, both for humans and automation. In complex, uncertain, and multi-variate problems, which are characteristic of command and control, these decisions must often be supported in order to achieve overall mission goals. There are three reasons why such high level decision making can be difficult: 1) Complexity of the problem, 2) Uncertainty, and 3) Opportunity costs of taking one decision over another.

The first of these reasons, complexity, applies because as the problem space becomes more complex, the problem itself becomes less structured and thereby less susceptible to analysis. Complexity in high level decision making exists due to multiple factors, among them, the ambiguity surrounding the different variables, the different possible courses of action, and the indirect impact of any decision to different organizations. A typical example of a complex system is the command and control center of a frigate, where information from the air, surface, and subsurface worlds is gathered, analyzed and acted on [1]. The system is complex because the worlds that the command center tries to control are dynamic and the multiple people/technologies have to integrate and analyze the information produced to achieve the frigate's mission.

The second of these reasons, uncertainty, is important since making an optimal decision is, in fact, selecting the decision with the highest probability of meeting the objectives. The different elements of a decision problem that are affected by uncertainty are a) the a priori information on the basis of which decisions are made, and b) uncertainty in the environment. Uncertainty in either or both of these elements contributes to decision uncertainty.

Finally, the third reason, opportunity costs, deals with the fact that selecting a particular decision for execution also means forgoing alternate decisions and their benefits. A decision maker needs to evaluate the possible tradeoffs (or

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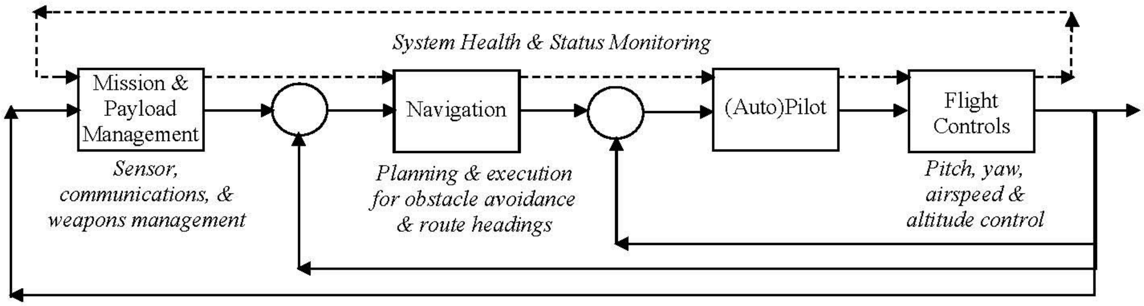


Figure 1: Embedded Control Loops for Unmanned Vehicle Supervisory Control

opportunities) in order to have a more complete cost-benefit analysis.

Other challenges to effective decision making include time constraints imposed by mission specifics, as well as interruptions arising from the system and/or the surrounding environment.

This paper describes an attempt to provide a decision support aid that addresses the difficulties in decision making specific to operator supervisory control of multiple heterogeneous unmanned vehicles.

II. Motivation

In order to more fully investigate the decision aids that would be needed to support judgment-based reasoning in the supervisory control of multiple unmanned vehicles, a prototype decision aid was developed for an automated target recognition task. The specific scenario included multiple unmanned underwater vehicles (UUVs) tasked to penetrate a harbor entrance, and then accomplish reconnaissance and surveillance objectives. In this scenario, a single operator would be required to control four UUVs via a part-time unmanned aerial vehicle (UAV) on a shared network.

After a comprehensive cognitive task analysis which resulted in the generation of functional and display requirements [2], a three-screen interface was developed to allow single operator interaction and supervisory control for the multiple unmanned vehicles (Fig. 2). This interface includes a map display (left), a health and status display (center), and a multifunctional, tasking display (right). The multifunction display of Fig. 2 is the focus for this paper, and more details about the entire interface and its design components can be found elsewhere [2][3].

The multifunctional tasking display provides mission planning and replanning functionality, as well as other tasking capabilities. It is the interface through which the operator receives information related to mission management as depicted in Fig. 1. Through the cognitive task analysis, we determined that to be able to effectively manage multiple vehicles, an automatic target recognition (ATR) system is needed that allows for suggested matches from an a priori database. However, because of all the problems previously mentioned with these difficult decisions, a simple suggestion is not adequate as the operator still has to decide whether the match is valid.

As part of the cognitive tasks analysis, decision ladders generated for the ATR task highlighted the fact that whereas certain steps were capable of being automated, the final decision of interpreting whether or not the EO-imagery contains a target of interest should not be automated. Figure 3 shows the decision ladder generated for the confirmation decision on the data received from the ATR.

From the cognitive task analysis and the resultant display and information requirements generation, we identified several potential obstacles to good decision making in the ATR task which included:

A. *System interruptions*

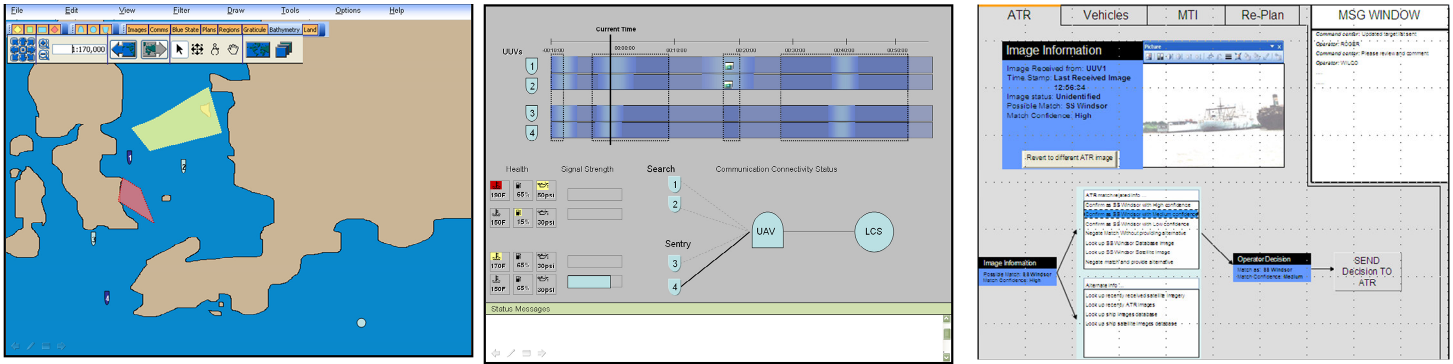
Because the UAV would not be continuously available, communication between the human operator and the UUVs would not always be available. Therefore, system interruptions will likely cause the operator to have to refamiliarize him/herself with the problem and decision at hand whenever system reacquisition occurs, including relevant information updates. If these interruptions are not properly addressed, they could cause the decision making process to be inefficient and erroneous.

B. *System complexity*

The incongruent limitations and capabilities of heterogeneous vehicles as well as complexity that exists due to the one operator-many vehicles configuration could make the decision problem overly complex. Increased problem complexity is also accompanied by volumes of information requiring analysis, a phenomenon that is likely to cause information overload. All of this implies an increased cognitive load that could saturate the operator and cause negative repercussions in terms of decision making.

C. *Time constraints*

Because the primary mission is one of intelligence, reconnaissance and surveillance for harbor patrol, time is a critical resource. Wasted time could mean that the operator might not be able to make decisions in order to meet the timing constraints, and therefore cause the overall mission to fail.



a) b) c)

Fig. 2. The three-screen operator interface: a) map display, b) health and status display, & c) tasking display.

A decision aid that alleviates these obstacles would play a significant role in improving not only human performance but system performance as well. Thus a useful decision aid would satisfy the following requirements:

- The decision aid should help the operator resume operations quickly after an interruption.
- The decision aid should reduce system complexity so that the human operator can spend more time analyzing information as opposed to trying to understand the problem.
- The decisions aid should allow the operator to backtrack in the decision process as the environmental conditions are always changing in real time.
- The decision aid should reduce the time it takes for an operator to make a decision.
- The decision aid should give the operator flexibility in making decisions by providing alternative methods by which to make decisions.
- The decision aid should be robust in the face of any uncertainty in the a priori information or the environment.

III. DCDT

The dynamic contextual decision tree (DCDT) was designed to meet the requirements specified above. The DCDT is an interactive decision aid, which assists in the decision making during surveillance. As highlighted in the motivation section, this decision aid is not an independent construct, but instead one that falls within the larger framework of a human/machine interface (Fig. 2, right side). In Fig. 4, the DCDT is shown embedded within the tasking display (in the bottom half of the display) which also contains system information in the top half of the display as well as an instant message window in the top right part of the display. The tasking display is tabbed so as to allow the operator to work on different tasks by switching to the appropriate tab. A notification system directs the operator's attention to the appropriate tab when information is received that requires the operator to act on it. The DCDT is itself composed of five elements; a) the information received from the system that initiates the decision making process, b) information boxes with links to sources of information, c) decision boxes that allow the operator to specify a decision, d) a summary of the operator's final decision, and e) a button for executing a final decision when one has been reached.

Traditionally, the term "decision tree" is used in reference to a tool for structuring the elements of a decision situation into a logical framework [4]. An alternative tool to a decision tree is an influence diagram which contains less information than a decision tree but is simpler to interpret. Both of these tools, however, are used for creating a model of the decision problem and therefore allow the human to plan and analyze the alternative decisions prior to selecting a final decision. Because decision trees and influence diagrams are planning tools, they are generally not used in real time. DCDTs, on the other hand, were designed in order to support real time decision making in a dynamic environment and therefore serve

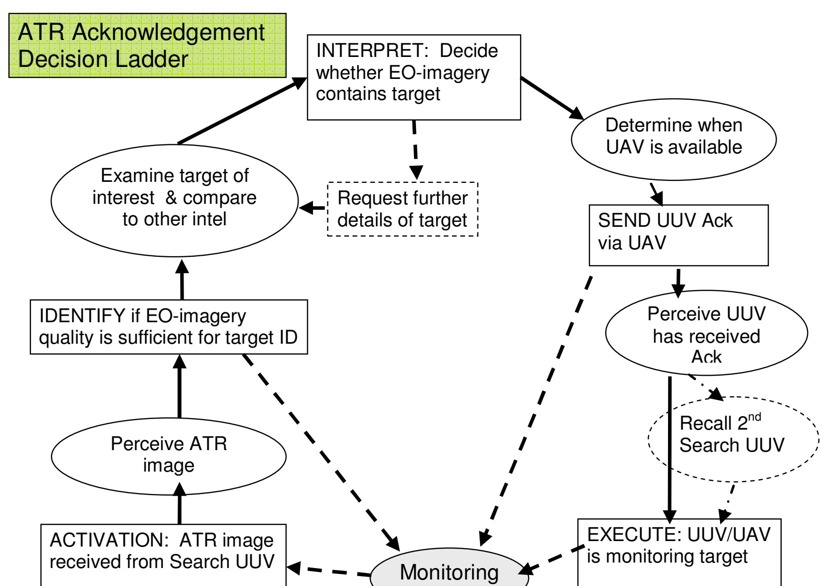


Fig. 3. Decision ladder of ATR acknowledgment

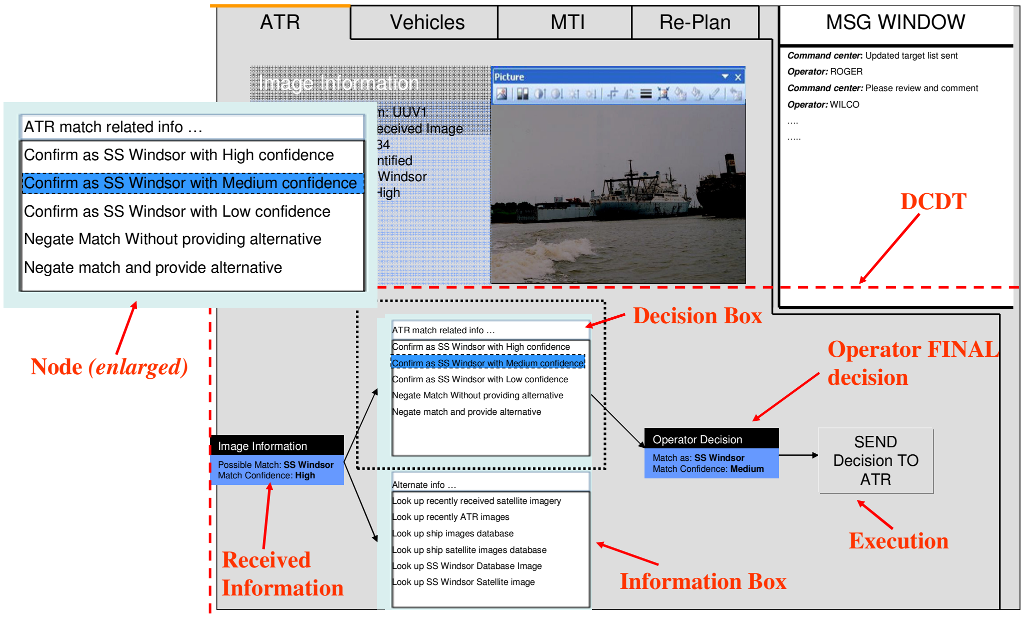


Fig. 4. Tasking display

a much different purpose than traditional decision trees or influence diagrams.

DCDTs are dynamic trees that essentially walk the operator through the decision process. The trees grow horizontally towards the right, and have a width of two at the most (i.e. the number of nodes at any row of the tree is at most two). A node, as seen in Fig. 4, is comprised of one or more actions, and because of the dynamic nature, clicking on an action within a node causes the tree to change accordingly.

Nodes present operators with two types of information (Fig. 5): 1) Those that contain a set of actions as a result of a decision (i.e., the decision box), and 2) Those that contain a set of actionable information sources which help in making decisions (i.e., the information box).

A. *Decision Box*

The decision box contains a list of possible decisions that the operator can make. At each point in the decision process, the decision box provides the operator with the available sub-decisions given previous ones. DCDTs provide sub-decisions that are not final decisions and final decisions that provide a response to the initial problem. Final decisions allow the operator to select the final match with a low, medium, or high confidence level as well as rejecting the match outright. Sub-decisions are intermediate steps towards a decision, when selected, and create two new boxes; a decision box and an information box (Fig. 6d). The new decision box contains a new set of possible sub-decisions such that the restrictions imposed by the last taken sub-decision are taken into account. Each new information box contains a new set of relevant information sources such that the restrictions imposed by the last sub-decision are taken into account.

B. *Information Box*

The information box contains a list of information sources that the operator can investigate in order to make a better decision. DCDTs display only the information relevant to the particular decision (or to the remaining sub-decisions as progress is made) as opposed to all the information available. Some of these information sources include examining other electro optical (EO) images or satellite images of the contact previously stored in a database, or looking at other imagery for other contacts that resemble the current contact in some way. Information sources are organized categorically, which makes them more easily accessible. This organization saves the operator time because it makes it clearer where to find specific information.

C. *Case Study*

Using the previous 4 UUV/1 UAV single operator scenario, we will illustrate how a DCDT works for the previously described ATR task.

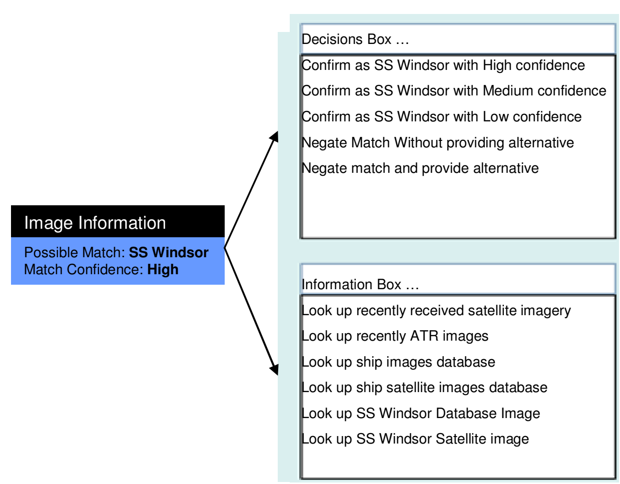


Fig. 5. Example screenshots of DCDT when information is first received

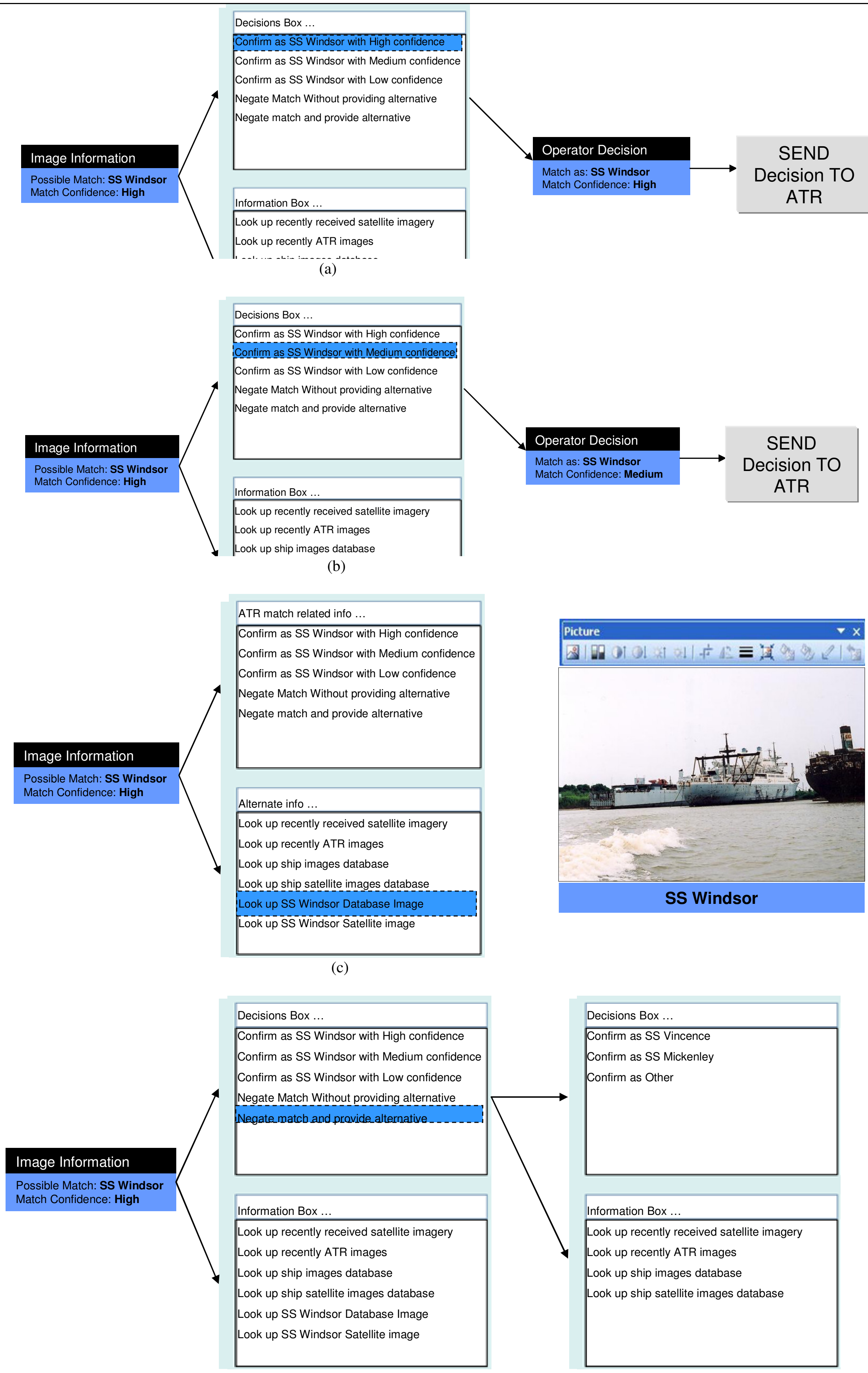


Fig. 6. Example screenshots of DCDT (a) if operator confirms ATR decision (b) if operator modifies confidence level only (c) if operator decides to look up extra information (d) if operator makes a sub-decision

Let us assume that the ATR software, after comparing electro-optical images of ships in the harbor with a database of target ships, finds a possible match. The possible match in this example is the SS Windsor, and the image and a confidence level in the match are sent to the operator. This in turn causes the tasking screen to display the electro-optical image received as well as a DCDT in the lower half of the screen as shown in Fig. 4. The DCDT first displays the information on the SS Windsor, summarized in a box on the left most node of the tree with arrows extending to the decision and information boxes as shown in Fig. 5, along with their previously discussed options. To better illustrate how the user can interact with the system, four different scenarios are presented:

Case 1: The operator agrees with the suggested match provided by the ATR and decides to confirm the match as correct. The operator would then click on the decision from the decision box labeled "Confirm as SS Windsor with High Confidence". This then causes an arrow to emanate from the decision box to a new box that describes the final decision as shown in Fig. 6a. The operator can review all this information before clicking on the submit button that will send the decision back to UUV.

Case 2: Due to the presence of fog in the harbor, the captured EO image is not as clear as it would normally be in clear weather. The operator, after scrutinizing the image and comparing it to database images of the SS Windsor, is fairly certain that the match is indeed correct, but the quality of the image leaves room for doubt. The operator would then represent the a priori information's uncertainty in his/her response by confirming the match with a confidence level of medium. The operator would then click on the decision from the decision box labeled "Confirm as SS Windsor with Medium Confidence". This will then cause an arrow to emanate from the decision box to a new box that describes the final decision that was arrived at as shown in Fig. 6b. The operator could then review all this information before clicking on the submit button that will send the decision back to the UUV.

Case 3: The operator is unsure that the match with the SS Windsor target ship is correct and would like to review an old image from the SS Windsor image database. The operator would then click on the information source from the information box labeled "Look up SS Windsor Database Image". This will then bring up the image of the SS Windsor that is available in the database as shown in Fig. 6c. The operator can then review this information source, and then select to review more information sources or make a decision if convinced of the match after reviewing the image.

Case 4: The operator decides that the match is incorrect and chooses to negate the match in order to seek an alternative. The operator would then click on the decision from the decision box labeled "Negate Match and Provide Alternative". This will then cause two new arrows to emanate, one to a new decision box, and another to a new information box as shown in Fig. 6d. The new decision box contains a new list of decisions that takes into account the fact that the operator has already decided to negate the previous match. The new information box also takes into account the restrictions imposed by the last sub-decision taken, and therefore contains only the information sources relevant to other ships and not the SS Windsor.

In the next section, we will describe the properties of DCDTs that make them helpful in making decisions.

IV. Properties of DCDTs

Recalling the requirements for a supervisory control decision aid that were generated in the motivation section, we now discuss the properties of DCDTs and demonstrate how the DCDTs satisfy those requirements.

A. *Simplifies Decision Problems*

DCDTs reduce the complexity of decision making by breaking down a decision into sub-decisions that are simpler to make. Complexity in decision making, as defined earlier, exists due to the lack of a problem structure which makes analysis difficult. This is addressed in the DCDT by stepping the operator through the decision process in a methodical manner, requiring simpler sub-decisions to be made at each step.

B. *Context dependent*

The DCDTs display only the sub-decisions and information that pertain to the underlying decision under consideration. First, this property satisfies the requirement of reducing the time it takes to make decisions, and does so by saving the operator from having to determine which information sources are relevant. In addition, this information is presented in an organized manner thus saving the operator valuable time that would otherwise be wasted. Also, because the trees are dynamic, the operator is presented with only the sub-decisions that are possible at any point in time. This automatically eliminates those sub-decisions that are not feasible, thereby reducing the complexity of the problem.

C. *Allows Traceability/Backtracking*

Because the sub-decisions that led to the current decision are displayed in the order they were made, the operator can trace back through these sub-decisions, therefore achieving

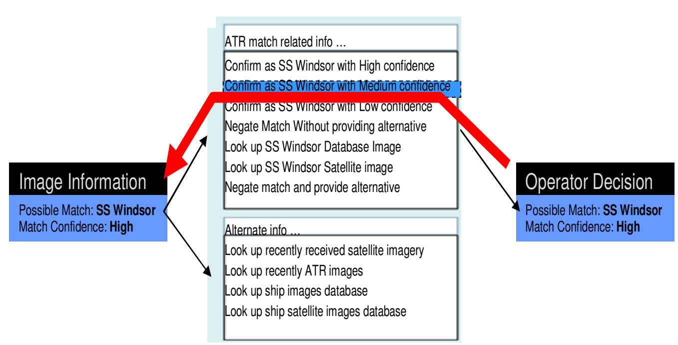


Fig. 7. Traceability property of DCDTs

traceability (Fig. 7). This traceability aids the operator in being aware at all times of the decision path he/she followed. The traceability property also allows for backtracking which was determined to be a critical consideration due to dynamic scenarios.

D. Interruption tolerant

As specified in the list of functional requirements previously generated, interruption tolerance is extremely important. In such command and control settings as multiple heterogeneous unmanned vehicle control, this aid is designed for, interruptions can occur all the time. Because the automation walks the operator through the decision process, the sub-decisions made by the operator are recorded. The DCDT therefore keeps track of the operator's progress through the decision process, and on resumption redisplays to the operator the tree as it was before the interruption. The operator is then able to refresh his/her memory with the sub-decisions, in the order that they were taken, and can resume the decision making process from the point last reached.

E. Flexible

DCDTs satisfy the requirement of being flexible by providing alternate methods by which to make decisions. Operators can select final decisions right away when the decision to a problem is clear, but they also can select sub-decisions when the operator requires a more detailed analysis. An example of this is the availability of decisions such as the "Negate match and provide alternative" selection, which provides access to other imagery and information sources.

F. Uncertainty Tolerant

By allowing the operator to make decisions accompanied by confidence levels, the decision maker can be more specific in his/her decision, thereby increasing the resolution of final decisions from a binary yes or no decision. This increased resolution allows operators to reflect the uncertainty in the a priori information or environment in their final decisions. Allowing operators to select confidence levels in their decisions provides situation awareness to other team members and commanders, who can then either augment the information (e.g., with additional intelligence) or seek additional information resources (such as satellite time) in order to obtain a decision of higher confidence.

In addition to meeting the requirements resulting from the cognitive task analysis, it is important that they also support good human factors principles including basic usability. For example, because DCDTs are displayed compactly in the same location on the screen and the information they contain is collocated, the operators need not flip through different windows or pop-up screens to reap the benefits. This allows the DCDTs to take advantage of the proximity compatibility principle which dictates that information sources that need to be related or compared should be positioned close together on the display, therefore requiring little scanning activity [5][6].

Also, because the whole tree is visible at any point in time, this avoids the operator from experiencing a tunnel vision effect [7] which occurs when the user can only see one part of a larger information space and thereby loses awareness of the rest of the information.

By satisfying the requirements specification for the decision aid as well as good human factors principles, DCDTs attempt to mitigate the obstacles to decision making previously described. It is important to note that DCDTs were designed specifically for an ATR acknowledgment process that has a clear decision path and sequential steps. Extending DCDTs to decision problems lacking these qualities would require a more extensive framework. A possible improvement would include increased automation that suggests decisions and information sources based on real-time intelligence and not just a predetermined set.

V. Conclusions

As the presence of unmanned vehicles becomes more prevalent, the management of sensors and payloads becomes increasingly important for mission success. This, in combination with a future vision of operators supervising multiple unmanned vehicles, creates a situation where decision making at the mission management level is a necessity. Such decision making, which requires reasoning and judgment, is difficult, both for humans and automation. Some form of decision support to aid human operators is therefore required if such human-machine interactions are to be efficient.

Requirements for a real time decision aid were generated by creating a decision ladder for the ATR acknowledgment decision problem. These requirements, in addition to good human factors principles, drove the design for the DCDTs which essentially walk operators through a decision making process.

The resultant properties of DCDTs included the ability to a) simplify decision problems, b) allow faster decision making, c) support backtracking, d) tolerate interruptions, e) be flexible in supporting decision making, and f) be robust under uncertainty. These properties satisfy the requirements for a decision aid that we first generated and make DCDTs suitable as an aid to support mission management level decision making.

In future work, human performance studies will be conducted to determine whether or not the DCDTs improve decision making performance, as well as what mix of sensors and information available promotes the best performance.

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