Cognitive Task Analysis for Maritime Collisions

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ABSTRACT

This study used Cognitive Task Analysis (Crandall, Klein, & Hoffman, 2006) to elicit expertise in collision avoidance at sea. The knowledge elicited was used to develop a decision-support tool. Watch officers are constantly fed with vast amounts of information and at the same time, they are required to draw conclusions about the time-critical situations at sea. The mental workload experienced can be reduced with a decision-support tool, which factors in relevant data, assesses the situation and computes the best course of action. Five experienced naval officers were interviewed and their expertise was elicited using the Critical Decision Method (Klein, Calderwood, & MacGregor, 1989). This was combined with information from a training facility, as well as information from (1) literature on collision avoidance and (2) manuals for navigation at sea. The information was organised and programmed into the iGEN Cognitive Agent, a decision-support architecture developed by CHI Systems (Zachary, Ryder, & Hicinbothom, 2000). The decision-support tool was designed to read key information from sensing devices, primarily the radar, about the position, speed and course of surrounding vessels. It then interpreted the situation. The recommendations from iGEN were then validated (these results are reported separately in another paper).

Keywords: Cognitive Task Analysis, Cognitive Systems, Maritime Collision Avoidance,

INTRODUCTION

A recent study of navigation accidents identified several situational factors related to human, task, system, and environment. It was found that task requirements related to anticipation, perception, criticality, and diagnosis were common factors (Gould, Roed, Koefoed, Bridger, & Moen, 2006). Chauvin, Clostermann, and Hoc (2008) also found that 55% of the young watch officers who participated in a study of situation awareness at sea performed a maneuver that was against regulations, and 34% performed an unsafe manoeuvre.

A large amount of information is constantly fed to the watch officers in a naval bridge team, and they will need to make critical decisions while navigating. To do so, they need to filter information and draw conclusions about time-critical situations as they assess the risk of collision with surrounding vessels, and determine the best course of action. Their mental workload can be reduced by using a decision-support tool, which factors in the relevant data, assesses the situation and computes the best course of action.

The objective of this study was to elicit the expertise in collision avoidance at sea, and use this knowledge to develop a decision-support tool for aiding decision-making. The elicited material was organized into an information flow and an advisory system was programmed using the iGEN software developed by CHI Systems (Zachary, et al., 2000). The advisory system was designed to read key information from sensing devices, primarily the radar, about the position, speed and course of the surrounding vessels. It then interprets the situation and suggests an action using the information flow reported in this study.

iGEN

The iGEN software is an integrated development environment that facilitates development, testing and deployment of cognitive agents (Zachary et. al., 2000). Cognitive agents, such as iGEN, are machines that mimic human cognition. CHI Systems, through their understanding of human expertise and experience in developing advisory systems, designed iGEN to support quick prototyping and development of advisory systems. Expert cognitive systems, which were developed using iGen, have been applied as training agents (Ryder, Santarelli, Scolaro, & Zachary, 2000; Zachary & Ryder, 1997), decision aids (Zachary, et al., 2000), and as a human substitute in hazardous environments (Zachary, et al., 2005).

The iGEN Cognitive Agent is modeled using COGNET, a human cognition model that integrates models from cognitive science, decision science and psychology. The COGNET model mirror concepts in the Human Information Processing model (Wickens & Hollands, 2000). The software engine, Blackboard Architecture for Task-Oriented Networking (BATON), interprets cues and places them in its memory. The information is then processed by various sets of cognitive rules before an action is decided and executed. The information processing mechanism can broadly be classified as declarative knowledge and attention management. Both are known to be exhibited by experts.

The iGEN software is intended to be used by a team consisting of a cognitive analyst and a software engineer. The software engineer is responsible for building the shell that translates information between the virtual world and the physical world. The parameters to be communicated are specified by the cognitive analyst. In addition to these parameters, the cognitive analyst builds the declarative knowledge and attention management in the BATON. The subsequent sections focus on how the cognitive analyst collects the information and designs the advisory system.

KNOWLEDGE ELICITATION

In this study, the requirements were elicited using Cognitive Task Analysis (CTA). The objective was to determine the tasks that the agent would support for the collision avoidance task. Specifically, the analyst identified declarative knowledge that was used in the situation; perceptual cues for sensing the external environment; thought processes expressed as GOMS-like compiled goal hierarchies; and actions exhibited by the Subject Matter Expert (SME). The knowledge was analysed and the challenges in building the advisory system were identified.

Five experienced naval officers (two active and three retired) were interviewed and their expertise elicited using the Critical Decision Method (Klein, et al., 1989). All participants had more than 10 years of experience in managing naval bridges. This was coupled with document reviews of (1) existing literature for the development of collision avoidance and (2) manuals for navigation at sea.

DOCUMENT REVIEW

Two themes were explored in the document review: collision avoidance systems and collision avoidance computation. The first theme investigated whether there were existing collision avoidance systems to avoid the reinvention of the wheel. It was found that there was no system that kept track of both higher and lower levels of cognitive activity. Grabowski and Wallace (1993) built an advisory system that supported the lower level cognitive skills (e.g. manoeuvring), but not the track-keeping of the vessel. Yang, Shi, Liu, and Hu (2007) developed a multi-agent-based decision-making system for solving the problem of collision avoidance. Each vessel was an independent agent with a set of operating rules that can negotiate the collision situation. They were working on a risk-evaluation model, which had little in common with this study where the advisory system would be tested empirically.

The second theme investigated techniques for computing collision avoidance. The Admiralty Manual of Navigation: BR 45 Volume 1 Chapter 17 (1987) offers some guidance on computation of relative velocity and collision avoidance. The chapter presents the use of “relative track” to compute the closest point of approach. If the closest point of approach is zero, there will be a collision. It also discusses the presentation and limitations of the radar of judging collision.

The International Regulations for Preventing Collisions at Sea, also known as the Rules of the Road, documents useful principles for collision avoidance during navigation, which can be expressed into collision avoidance computation

(*Admiralty Manual of Navigation: BR 45*, 1987, Volume 4 Chapter 9; Allen, 2004). This contains 38 collision avoidance rules, which are adopted by 97% of the world's shipping tonnage (Allen, 2004). It was first written during the Industrial Revolution in the 19th Century, when collision and near-collision rates were increasing.

INTERVIEWS

A semi-structured interview technique, Critical Decision Method, was used to interview the experts (Klein, et al., 1989). They were asked to recall critical incidents of collision avoidance that they had experienced. They then broke the task into three to six steps and briefly discussed each sub-task. The interviewer identified the sub-tasks that imposed high cognitive load and probed deeper for (1) goals and shifts in goals; (2) perceptual cues needed in making the decisions; (3) difficult mental tasks in the situation; and (4) actions taken to overcome the challenges.

Seven stories that capture the essence of the expertise in avoiding collision at sea were collected. In all stories, the situation and the action taken by the SME were first described. The goals, cues and mental tasks in handling the situation were elaborated. Table 1 presents one of the stories where a naval ship was investigating a trawler, and the trawler unexpectedly charged at the naval ship. Based on the content analysis of the stories, we then derived the knowledge and decision rules that were used by experts in collision avoidance, which were later programmed using iGEN.

ANALYSIS

The knowledge elicitation process identified five main challenges in designing an advisory system for the naval bridge. They are: (1) knowledge management, (2) shifts in priorities, (3) situation interpretation, (4) self-awareness, and (5) level of automation. The iGEN cognitive agent was assessed for its ability to address these issues, and it was concluded that the first four challenges can be addressed using the iGEN cognitive agent.

We noted that members in the bridge team were manually processing data. However, in many cases the procedures can easily be automated. As an example, the radar automatically detects contact within a specified range, but it does not compute the risk of collision, unless the radar specialist physically acquires the contact by clicking on it. Although the radar can automatically acquire targets, this is not useful for piloting in Singapore waters, as the large number of vessels would quickly overload the system without helping the watch officer. Hence, an automated cues management system would be useful to help the watch officer focus on the information that has priority.

KNOWLEDGE MANAGEMENT

The blackboard capability in the iGEN cognitive agent allows the designer to specify the relationship between objectives. There are two main relationships:

hierarchy and links. Hierarchies mimic human information processing, while the links store associations that human creates between objects. The hierarchy supports quick programming. During programming, the designer can select from a pre-defined drop-down list (generated from the blackboard). The links allow fast information retrieval when running the advisory system. When the advisory system receives a new cue, there is no need to run through all objects to find an item. The program starts searching for items that has a relationship with the cue.

Table 1. A story on a near-collision situation

Challenging situation and action(s) taken – During a patrol mission the SME was instructed to investigate a vessel of interest (VOI), a suspicious trawler which was ahead of the SME's ship. The bridge team was tasked to get closer to the VOI, so that the Commanding Officer could question their intent by shouting across. As his team approached the VOI at about 12 knots, the VOI turned and headed towards his vessel. The SME noticed that the VOI might come into a light collision with his vessel and ordered his bridge team to reverse at 10 knots to avoid the collision. **Goals & sub-goals shift in goals** - The initial goal was to ensure the territorial integrity of Singapore by preventing illegal entry into Singapore's waters. This was to be achieved by investigating any potential threats. When the VOI charged at the naval ship unexpectedly, the SME was concerned with the safety of his vessel. At this stage, safety became the active primary goal. Safety was previously a dormant goal, but was activated when the vessel and its occupants' safety was compromised. **Cues –** Three cues helped the SME to identify the danger and make his decision. First, the movement of the VOI was unusual. Typically, vessels will cooperate and slow down when stopped by the naval authority. Second, the distance to the VOI as visually assessed by the SME to be relatively near. This meant that the SME would need to act quickly. Third, the SME judged that the relative speed of the VOI heading towards his ship was about 15 knots. At this instance, the naval ship had slowed down to 6 knots. The combined speed was judged to be too fast for a starboard turn. **Strategies and mental tasks** - The SME made use of his knowledge of his vessel. He was aware of that the vessel was capable of reverse propulsion and he applied this knowledge appropriately. A novice watch officer may not be as competent and choose to turn port or starboard. This decision would have resulted in a collision because his vessel had slowed down to 6 knots. Also, a novice watch officer may not know that in situations pertaining to safety to the ship, he can override an order, if he sees that the ship is in danger. The last order given by the Commanding Officer was to close up to investigate. A novice watch officer may seek the Commanding Officer's approval to mitigate the collision situation instead.

The iGEN cognitive agent can also support simple computations. Simple computations can be performed by the iGEN cognitive agent, while difficult mathematics can be passed on to the external environment for computation. The program can also retrieve information from databases. Every vessel has a record of its own capability such as maximum speed and performance at different speed. Such information can be programmed to be used by BATON for making decisions. Vessels that might pose dangers can be computed by iGEN based on the information derived from the ship's sensors and other databases. Such vessels can then be highlighted to help watch officer in processing the most important data.

SHIFTS IN PRIORITIES

The inherent goal for collision avoidance is safety. When safety is not compromised, bridge teams set their attention to navigation and missions. For navigation, there is a planned route and the bridge team operates the vessel from point to point based on the planned route. But should safety concerns arise, e.g. an incoming vessel on collision course, the bridge team must alter the route, and safety becomes a top priority.

In addition to achieving safety, naval vessels execute missions. Three types of naval missions were reported in the interviews: convoy operations, investigation, and live firing exercises. The navigation in each of these missions is different. In one story, the expert led the last vessel in a convoy and experienced a near collision with a vessel that was laying cables. Following a convoy may still be considered as point-to-point navigation but there are additional requirements imposed on the bridge team. Conflicting goals might arise and usually, safety will take priority over other goals.

The iGEN cognitive agent possesses good modules for supporting goals. Goals are triggered when a combination of conditions are met. There is a "trigger condition" module that facilitates the input of these conditions. The iGEN software also supports the shifts of goals using a "priority" feature. Each goal has a "priority", which is a number. The various goals will all be "calling for attention". The goal with the highest priority gets the attention. This is in analogy with Selfridge's Pandemonium model (Selfridge & Neisser, 1995).

SITUATION INTERPRETATION

In the story presented in Table 1, the expert thought that the sudden turn of a vessel was irregular and could be a hostile act. A sudden turn can be detected by analyzing differential velocities from radar plots. Challenging incidents that experts face can be analysed, interpreted and programmed into the advisory system. In addition to the incidents, the characteristics of the vessels can also be taken into account.

Situation interpretation refers to processes which deal with tacit information. These are the processes which we (operators) are well familiar with, but do not necessarily think about, because we have become so used to them. One good example is tying your tie or shoe laces, or similar. We know how to do it, but since the procedure has become automated in our motor skills, it is difficult to describe in words.

The iGEN cognitive agent can mimic our cognitive abilities if it is fed the perceptions one receives from the environment. Features of challenging situations can be programmed into the system. The difficulty is to know whether the information from the sensors is good enough, complete, and timely so that the implications are clear with sufficient time to make decisions. The advisory system is good only if the inputs are complete, accurate, and timely. If the sensing technology produces better results than the human, the advisory system will be able to perform better than the human. The contrary is also true.

SELF-AWARENESS

It was noted that the quality of the decisions made by the SMEs hinge on their knowledge of the capabilities and limitations of the vessel they operate. The SME, who knew that his vessel is capable of doing reverse propulsion, was able to quickly move away from the hostile vessel, see story in Table 1...

In designing the advisory system, one requirement would be self-awareness. The advisory system should be aware of its maximum speed, advance and transfer at different speeds, and stopping distance. Such information can be stored in the iGEN cognitive agent and used for computation of “what-if” scenarios.

The database can also be used for diagnosing problems in the vessel. For example, one SME spotted a rotational radar drift. The interpretation would be that the vessel was spinning on the spot. But it was not! Something was wrong with the radar. Self-diagnostic features can be added by checking the data against other sources of data and computing if these data, as a whole, conform to natural effects and/or those in normal operations.

LEVEL OF AUTOMATION

The most difficult issue in this study was related to the level of automation. Sheridan (2002) discussed varying degrees of automation ranging from no technology aid to an aid that performs the task automatically and informs the human only when asked. The advisory system can possibly have an auto-pilot mode, where the commander is informed only about the decisions made by the advisory system. On the other extreme, the advisory system could be used to only provide the expert with information; and all decisions are then made by the human commander.

Currently, the watch officer has to manually take charge of situations, control the bridge team and decide the own ship’s actions at sea. The navigation task is at the lowest degree of automation. In the story in Table 1, the watch officer did not seek the Commanding Officer’s approval before executing his decision. Could we likewise allow the automation to take control and steer the ship away from danger?

This is one issue which iGEN was unable to address. iGEN can be used only to a specified level of automation. There are no features or modules in the iGEN software that allow the operator to select the level of automation. It is also difficult to design for the advisory system to take over when the bridge team is incapacitated.

When iGEN was conceived, the focus was mainly on expert thinking. Most expertise literature addressed the individual. In addition, to facilitate operation at various levels of automation is typically difficult to achieve. The current iGEN requires one to determine the level of command and autonomy given to the advisory system at the early design stage. While it may be possible to include the selection of different level of automation, this requires more complex programming.

To conclude the evaluation, we would like to highlight that the advisory system is only as good as the rules that are programmed into the system. Despite having identified the potential of using iGEN for building our advisory system, it is important to note that advisory system works based on the procedural rules identified. While these rules work most of the time, it is still susceptible to most failure like all other automation. In one of the stories, the SME decided on an action that did not comply with the navigation traffic rules, but was a safer decision. The question then arises if there are categories of scenarios which are better not to be controlled by automation. Rigorous validation and testing should be conducted.

DESIGN OF THE ADVISORY SYSTEM

The Cognitive Task Analysis led to the development of an information flow map, which was subsequently programmed into the iGEN cognitive agent. The advisory system was designed to read the measurements from other navigation tools such as the radar, sonar, AIS (Automatic Identification System), and ECDIS (Electronic Chart Display and Information System). It interprets the data (position, speed course, class, etc) for nearby vessels and assesses if there will be a risk of collision. The conclusion of the assessment is communicated to the watch officer in the form of alerts and suggestions.

The Advisory System will interpret the information and make sense of the situation. The interpretation is based on the findings derived from the Cognitive Task Analysis. Figure 1 shows the information flow for assessing the collision situation. When a vessel of interest (VOI) is picked up by the radar, the tool determines if the VOI is within a tracked zone. The concept of having a tracked zone is to sort out VOIs that will not be in the path of the own vessel in the near future. This reduces the information processing load. The remaining VOIs, which are within the tracked zone, are evaluated for their risk of collision. This is done by examining historical data of each vessel, their closest point of approach (CPA), and time to CPA.

If a VOI is judged to have a potential risk of collision, the system assessed if there was a prior assessment of the vessel. If the VOI has been evaluated, and a corrective action has been taken, the CPA should be increasing. This is performed to ensure the VOI is conforming to the expectations.

If the VOI has not been evaluated, the system alerts the watch officer of the vessel. It then computes if the watch officer has the right of way. The watch officer does not have the right of way when (1) the VOI is a big vessel with low maneuverability; (2) the VOI is not a power-driven vessel; (3) the VOI is on the starboard/right; and (4) the VOI is ahead and both vessels have to take action to mitigate the situation. If the watch officer has the right of way, the system would check if the CPA is increasing and advise if the VOI is giving way. Otherwise, the system would inform the watch officer that he needs to prepare to give way. The system would then evaluate the course of action and advise the watch officer to take a safer route for avoiding the collision. The corrective action will be determined by analyzing the position of the VOI (ahead, behind, left, or right), the obstacles in the path, and the time to make the maneuvers.

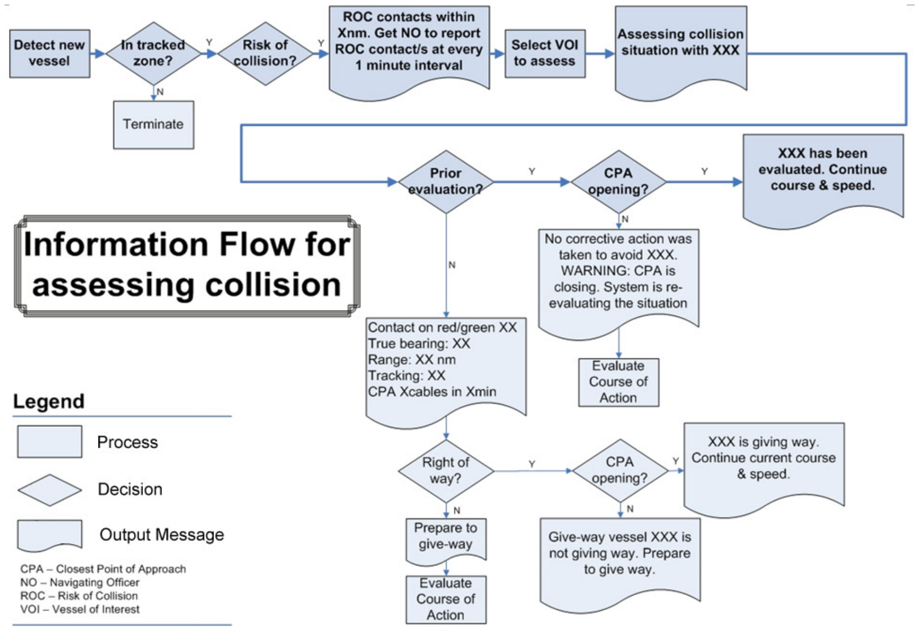

Figure 1. Information flow for assessing the risk of collision.

CONCLUSION

This paper demonstrates the application of Cognitive Task Analysis for the design of a first-of-its-kind system for avoiding collision at sea. Five naval officers were interviewed using the Critical Decision Method and the goals, cues, mental strategies, and actions considered in the stories were analyzed. The findings were used to develop an advisory system using the iGEN software.

Five main challenges for the construction of the decision-support tool were identified, and iGEN was assessed for its ability to address these issues. The five challenges are: (1) level of automation; (2) knowledge management; (3) shifts in priorities; (4) situation interpretation; and (5) self-awareness. Only the level of automation could not be mitigated using the iGEN cognitive agent.

The findings from the Cognitive Task Analysis were also translated into an information flow map, which was subsequently programmed into an advisory system. The advisory system has been validated and will be reported in a separate paper. In the validation, the decisions generated by the tool were first compared with the decisions made by officers in a training simulation and later critique by a panel of experts. It was found that the tool was able to identify imminent dangers and the situations that the officers should attend to (83% similar identifications). The decisions made were rated to be better than the decisions made by the trainees. However, further studies need to be conducted to improve the resolution of the decisions and the scope of decision scenarios.

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