Augmenting the Operator Function Model with Cognitive Operations: Assessing the Cognitive Demands of Technological Innovation in Ship Navigation

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***Abstract*—The increasing technological sophistication of ship navigation systems may significantly alter the skills, knowledge, and strategies involved in navigating large ships. Many examples in other domains illustrate the dangers of technology-driven innovations. These examples show that without a systematic method to detect design flaws and training requirements, technology-driven designs may degrade rather than enhance maritime safety. The operator function model (OFM) provides the basis for examining technological innovations; however, the OFM does not describe specific cognitive demands. Augmenting the OFM with a description of cognitive operations provides a structured cognitive task analysis tool-OFM-COG-that can identify the design and training requirements needed to safeguard system performance. This approach identifies how to tailor designs, develop training, and adjust qualifications to minimize the human errors that might otherwise accompany technological innovation. This paper shows how OFM-COG can catalog differences between traditional navigation systems and those augmented with electronic charts and collision avoidance systems. Specifically, it examines the cognitive demands of collision avoidance and track keeping, with and without advanced technological aids. This analysis demonstrates that some advanced radars may in fact increase the likelihood of certain collisions, and that the current certification process does not reflect the cognitive demands of the new technology. The analysis also indicates that electronic chart display and information systems (ECDIS) can reduce the redundancy that has served to make traditional systems quite reliable. Drawing upon these examples, this paper describes OFM-COG and demonstrates how this novel, model-based analysis technique can document the cognitive implications of technological innovations.**

***Index Terms*—Automation, cognitive risk analysis, failure analysis, operator function model navigation.**

I. ADVANCED TECHNOLOGY AND MARITIME NAVIGATION

NAVIGATION of large ships involves many inherent difficulties. Because of the ship's tremendous inertia, all maneuvers must be carefully planned in advance. In addition, an array of imperfect information sources makes inferring the intentions and future courses of other ships problematic. These challenges, combined with the potentially disastrous consequences of incorrect decisions, make the navigator's job a singularly stressful one. This stress is magnified by the multiple, often competing tasks and responsibilities of navigating a ship, all of which must be carefully coordinated. While technological innovations seek to ameliorate these difficulties, new navigation technologies may also burden the human operator with increased cognitive demands.

The mariner will confront a range of new technology in the coming years. One popular innovation integrates a global positioning system (GPS) with digital charts to create electronic chart display and information systems (ECDIS). These technological innovations, combined with existing advanced maritime navigation systems (e.g., Automatic Radar Plotting Aid) tend to reduce repetitive physical activity while potentially increasing the mental demands made on the crew. The reduction in physical demands suggests the possibility of reducing the number of crew required on the bridge from as many as four people (captain, watch officer, helmsman, and lookout) to one. Recent studies suggest that under proper conditions, workload declines and performance rises with one-person operations [1]; however, this research has addressed only routine performance, and has not considered more stressful conditions. Studies in other domains suggest that poorly designed automation may reduce workload under routine conditions, but can actually *increase* workload during stressful operations [2], [3]. In addition, computer-based decision aids can also introduce new cognitive demands such as the need to monitor more ships during collision avoidance, to form mental models of the new technology, and to perform complex mental scaling and transformations to overcome the limits of electronic versions of paper charts. Although problems abound, properly implemented, these technologies promise to enhance ship safety as they eliminate time-intensive, repetitive, and error-prone tasks.

While technology has the potential to eliminate many simple tasks, historical data concerning shipping accidents indicate that many navigation errors result from misinterpretations or misunderstandings of the signals provided by technological aids such as collision avoidance systems [4]. Moreover, Perrow [5] notes that poor judgment in the use of technological aids contributes to many maritime accidents. These findings suggest that

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poorly designed and improperly used technology may jeopardize ship safety. In addition, as increasingly sophisticated navigation technology works to eliminate many physical tasks, complex tasks may appear to become superficially easy, leading to less emphasis on training. Further, navigational knowledge and skills may degrade because they are used only in rare, but critical, instances. Advanced technologies may also introduce new phenomena that affect mariner decision making, such as over-reliance on a radar display to steer a ship. In this situation, if the display fails to contain the information necessary to specify operator actions, errors will result [6], [7]. Thus, it is clearly important to understand the cognitive tasks involved with advanced navigation technology in order to guide design and training development. This paper describes how the operator function model (OFM) can be augmented with a description of cognitive tasks. This approach, termed OFM-COG, identifies how to tailor designs, develop training, and adjust qualifications to minimize human errors that might otherwise accompany technological innovation. To demonstrate how OFM-COG functions, we will show how automation changes the cognitive demands of ship navigation.

II. EXTENDING OFM TO ADDRESS THE COGNITIVE DEMANDS OF ADVANCED TECHNOLOGY

Traditional approaches to task analysis have been oriented largely toward the progressive description of jobs and tasks, emphasizing the observable aspects of performance [8], [9]. These methods have not kept pace with the increasingly cognitive nature of jobs, leading to a gap between the ability to analyze human performance and the information needed to support equipment design and mariner training [10]. Many other researchers have identified similar concerns in other domains, and the development of cognitive task analysis techniques has become an important research issue [11]–[15]. As maritime jobs come to involve increasingly complex technology, it is necessary to develop cognitive task analysis techniques to describe how this technology affects mariners' cognitive tasks, and to design equipment, training, and licensing procedures to reflect these changes.

A. Operator Function Model

The OFM describes and/or prescribes the role of an operator in a complex system [16]–[18]. OFM provides a framework for a precise specification of what information the operator will need, how it should be combined, and when it should be displayed. Furthermore, OFM details how this information must be transformed to support system operation [18]. Recently, this model has been used to identify training needs and decision support [19], [20]. Specifically, OFM has been used to differentiate between generic process-control knowledge, process-specific knowledge, and interface-specific knowledge. Thus, the OFM should help identify potential design flaws, training requirements, and qualification standards associated with the human role in ship navigation.

The OFM draws upon discrete mathematics to characterize operator activities as a network of nodes that are linked by arcs. The nodes and arcs represent finite-state automata, which provide a formal structure for system analysis. Fig. 1 shows the basic elements of the OFM. Each node represents an operator activity. The arcs that link the nodes represent the triggers or transition conditions that initiate, terminate, or sequence activities [16]. These triggers can originate from outside the system or they can represent the dynamic relationship between activities. State transitions can be nondeterministic, and so are able to represent operator choice in selecting which activity to pursue. Because the state transitions can be nondeterministic, the OFM can also express the stochastic relationships between triggers and state transitions. The flexibility of the finite-state automata enables the OFM to accommodate a variety of operator control strategies, while capturing the environmental and system constraints that shape behavior.

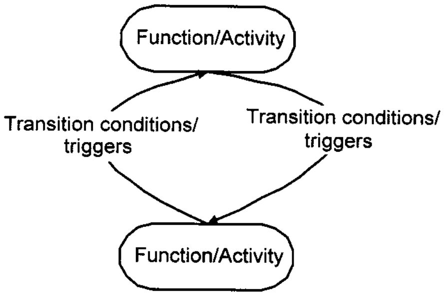

Fig. 1. Relationship between basic elements of the OFM.

The network of operator activities (nodes) and transition conditions (arcs) can be decomposed hierarchically, with the levels of the hierarchy representing the activities at different levels of abstraction and detail. At each level of the hierarchy, nodes can also be arranged heterarchically. The heterarchy represents activities that can occur in parallel, or alternate activities that are available to the operator. Additionally, a recent development to OFM is a well-defined set of properties that describes the ordering of activities [16].

At the top levels of an OFM hierarchy, the nodes represent abstract, high-level functions that describe overall activities. The levels of the hierarchy are defined so that functions are decomposed into subfunctions, tasks, and control mechanisms [21]. For example, activities related to maritime navigation can be decomposed from overall system functions, such as "Course execution," to the level of specific control actions, such as adjusting the gain on the radar. Activities at a higher level of the hierarchy specify *why* an activity is being performed (the operator's goals) and activities at lower levels specify *how* the activity is performed. The appropriate number of levels to be included in an OFM hierarchy depends on the particular application, with a detailed analysis of a more complex system requiring more levels than a high-level analysis of a simple system. The flexibility of the hierarchic structure allows the development of an OFM that has the detail necessary for many different types of analysis. A more complete description of the OFM methodology can be found in [22].

B. Consistent Vocabulary for Cognitive Operations

OFM defines operator activities, transition conditions, interrelationships between operator activities, and overall system

TABLE I
MILLER'S COGNITIVE TASK TRANSACTIONS AND THE HUMAN INFORMATION PROCESSING RESOURCES THEY DRAW UPON

Cognitive Agent Task	General Category of Information Processing	Human Information Processing Resources
1. *Input select.* Selecting what to pay attention to next.	Acquisition	Selective attention, Perceptual sensitivity
2. *Filter.* Straining out what does not matter.	Acquisition	Selective attention
3. *Detect.* Is something there?	Acquisition	Perceptual sensitivity, Distributed attention
4. *Search.* Looking for something.	Acquisition	Sustained attention, Perceptual sensitivity
5. *Identify.* What is it and what is its name?	Acquisition/Interpret	Perceptual discrimination, Long-term memory, Working memory
6. *Message.* A collection of symbols sent as a meaningful statement.	Handling	Response precision
7. *Queue to channel.* Lining up to process in the future.	Handling	Working memory, Processing strategies
8. *Code.* Translating the same thing from one form to another.	Handling	Response precision, Working memory, Long-term memory
9. *Transmit.* Moving something from one place to another.	Handling	Response precision
10. *Store.* Keeping something intact for future use.	Handling	Working memory, Long-term memory
11. *Store in Buffer.* Holding something temporarily.	Handling	Working memory, Processing strategies
12. *Compute.* Figuring out a logical or mathematical answer to a defined problem.	Handling	Processing strategies, Working memory
13. *Edit.* Arranging or correcting things according to rules.	Handling	Long-term memory, Selective attention
14. *Display.* Showing something that makes sense.	Handling	Response precision
15. *Purge.* Getting rid of the irrelevant data.	Handling	Selective attention
16. *Reset.* Getting ready for some different action.	Handling	Selective attention, Response precision
17. *Count.* Keeping track of how many.	Handling/Interpretation	Sustained attention, Working memory
18. *Control.* Changing an action according to plan.	Handling/Interpretation	Response precision
19. *Decide/Select.* Choosing a response to fit the situation.	Interpret	Long-term memory, Processing strategy
20. *Plan.* Matching resources in time to expectations.	Interpret	Working memory, Processing strategy
21. *Test.* Is it what is should be?	Interpret	Perceptual sensitivity, Working memory, Long-term memory
22. *Interpret.* What does it mean?	Interpretation	Long-term memory, Sustained attention
23. *Categorize.* Defining and naming a group of things.	Interpretation	Long-term memory, Perceptual sensitivity
24. *Adapt/Learn.* Making and remembering new responses to a learned situation.	Interpretation	Long-term memory
25. *Goal image.* A picture of a task well done.	Interpretation	Long-term memory, Processing strategies

functions. OFM was developed to prescribe the activities required for adequate performance without describing the cognitive processes associated with those tasks [23]. This provides an efficient tool to examine the role of procedural and situational constraints on operator activities. It does not, however, indicate the specific cognitive demands associated with operator activity. Yet, such cognitive demands are critical for many systems. To establish the cognitive demands imposed on an operator by specific activities requires analysis beyond that currently supported by OFM. We have developed an approach, OFM-COG, which augments the OFM by describing the specific cognitive tasks and associated mental demands of the activities described by the OFM. Our approach leverages OFM's description of domain-specific procedural and situational constraints to identify relevant domain-independent cognitive constraints that may affect performance. We use OFM to link basic psychological findings to the operational context with the aim of developing insights regarding the cognitive implications of technological innovations. OFM identifies the required operator activities and OFM-COG examines the mental demands of those activities.

A cognitive analysis requires a consistent vocabulary for mental activities [24]. Miller [25] studied this problem extensively in a project for the US Air Force concerned with developing a generalized taxonomy of human task performance. The result of Miller's work was a list of generalized information-processing task transactions, which are shown in Table I. These tasks are not a model of human cognition, but rather, a description of the information transformations and control activities needed for system operation (see [25] for more complete definitions.) We have adopted Miller's terminology for OFM-COG because it offers an analytic and descriptive framework that is consistent with the OFM method of activity analysis.

With OFM-COG, the activities, characterized as finite-state automata in the OFM, are further analyzed according to the 25 generalized information-processing transactions of Miller, which are organized into three categories: 1) information acquisition, 2) handling, and 3) interpretation. Information acquisition and handling tasks tend to depend upon perceptual sensitivity, working memory, and response precision. In contrast, information interpretation tasks tend to depend on long-term memory (expertise) and processing strategies. Miller uses generic terminology to describe information-processing transactions so that the approach can be used to describe *either* human *or* machine functioning. For this reason, the tasks in Table I are labeled "Cognitive Agent Task," where agent can refer to either a technological aid or a human. The principal advantage of using Miller's approach for task analysis and description is parsimony—it does not postulate task-specific cognitive processes, such as situational awareness.

Each cognitive task transaction demands certain information-processing resources of the humans performing them. The third column in Table I identifies the range of human information-processing resources, which are derived from generally accepted models [26], [27]. They include the following:

1) perceptual sensitivity;
2) perceptual sensitivity;
3) distributed attention;
4) distributed attention;
5) working memory;
6) long-term memory;
7) response precision.

Other taxonomies of cognitive tasks exist and could be used to code the cognitive demands, but the information processing approach provides a useful starting point [28]–[30]. These resources should be interpreted in the context of recent research that has demonstrated the importance of processing strategies and their dependence on information representation [31]–[33]. More specifically, the actual cognitive resources demanded by a task will depend on the computational constraints built into the tools available to the mariner [34].

C. Operator Function Model and OFM-COG for Ship Navigation

The information for the OFM and the cognitive analysis was collected during a series of shipboard observations, interviews with navigation experts, discussions with instructors at maritime training academies, and an examination of technical training manuals. This iterative process began with shipboard observations, which were used to define high-level functions. Further observations and interviews refined these functions and identified subfunctions and triggering conditions. Examining ship navigation activities using OFM reveals that navigation can be described by several high-level functions. Each of these functions can be broken down into subfunctions. Together, the functions and subfunctions represent a normative model of ship navigation, and indicate the required activities and triggering conditions associated with navigation. Fig. 2 shows the high-level functions and their interrelationships. Fig. 3 shows the subfunctions associated with the high-level function "Target Evaluation." The complete description of the high-level functions and subfunctions associated with ship navigation is included in [10].

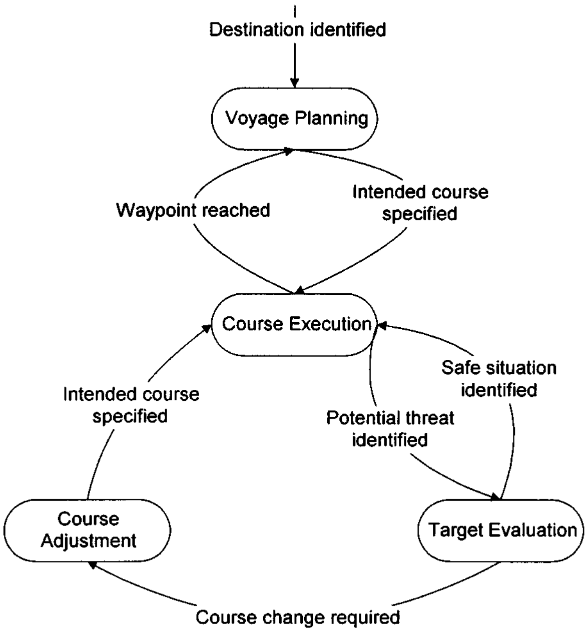

Fig. 2. OFM for ship navigation composed of a network of functions and transition conditions.

The functions shown in Fig. 2 consist of Course Planning, Course Execution, Target Evaluation, and Course Adjustment. Course Planning identifies course changes given the final destination and waypoints that must be reached. Course Execution represents the activities associated with ensuring that the ship proceeds along the intended course. As the ship advances, potential threats may be identified which trigger the Target Evaluation function. Target Evaluation represents the activities associated with evaluating whether an actual threat exists. If a ship or other obstacle threatens ship safety, then the need for a course change triggers the Course Adjustment function. Course Adjustment determines a new course, and this revised course triggers Course Execution and the voyage continues. These functions provide a very general description of the essential aspects of ship navigation.

Each high-level function can be hierarchically decomposed into subfunctions, and an examination of these subfunctions provides a more detailed description of voyage planning and navigation. For example, Fig. 3 shows the subfunctions that support "Target Evaluation." The activation of these subfunctions depends on the triggers for "Target Evaluation." For instance, the subfunction "Identify Target" becomes active when a potential threat has been identified. The output of this subfunction depends on a number of variables, including the immediacy of the

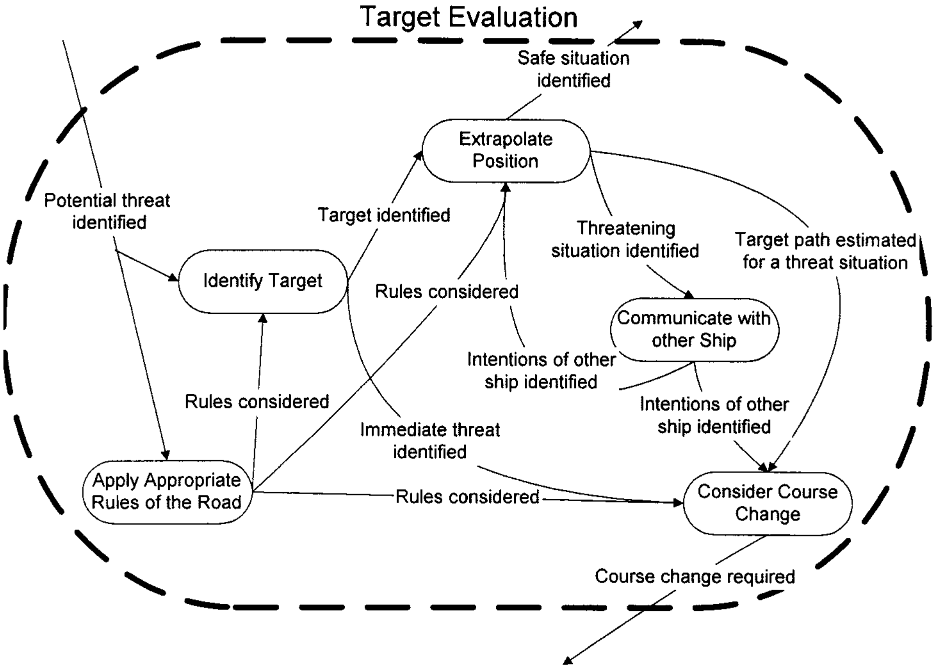

Fig. 3. OFM subfunctions for target evaluation.

threat, the estimated path of the other ship, the rules of the road, and desired safety margins. Like the "Identify Target" subfunction, each subfunction becomes active in response to conditions shown as arcs. These arcs reflect the system conditions that were changed by functions, subfunctions, or external events. The arcs connecting the system states are triggers that initiate subfunctions. For example, "Extrapolate Position" provides a best estimate of the future course of the potential threat and this triggers "Consider Course Change" if the extrapolated position poses a danger to the vessel that would require a course change. The subfunctions and the arcs that link them illustrate how the subfunctions interact to represent the dynamically changing operator activities.

At the level shown in Figs. 2 and 3, the OFM prescribes functional requirements for navigation and route planning. These represent system requirements that remain the same with any type of technology. Thus, this network does not depend on the type of technology available for navigation. As technology changes, the role of the mariner in each of these activities may change, but the same activities must be performed, with some of these activities accomplished by technological aids. Thus, Figs. 2 and 3 provide a formal structure to analyze how technology might affect navigation and voyage-planning. While the relatively abstract representation of the system shown in Figs. 2 and 3 remains constant regardless of changes in technology, a more detailed representation will show the effect of technology on cognitive activities. The lowest levels of a very detailed OFM representation could specify the specific interaction syntax required by a particular interface for a particular piece of technology.

OFM represents only activities and the conditions that trigger them, not the cognitive demands associated with these activities. OFM-COG expands OFM using Miller's cognitive task transaction vocabulary to describe the cognitive demands of each OFM subfunction. OFM provides a well-defined structure to describe operator activities, and Miller's cognitive task transactions help catalog the cognitive demands associated with these activities. Table II lists the cognitive tasks and demands associated with one of the subfunctions depicted in Fig. 3, "Identify Target." The cognitive transactions and associated information-processing resources all derive from Table I. OFM-COG identifies the cognitive tasks and the information-processing resources associated with each subfunction. OFM-COG also identifies the tasks and environmental demands that may affect human performance. For example, Table II shows that OFM-COG describes "Identify Target" in terms of three cognitive tasks. The information processing resources associated with these tasks include long-term memory, perceptual sensitivity, and sustained attention. The prevalence of long-term memory indicates the strong influence of experience and training in identifying the nature of a threatening ship. Important task and environmental factors affecting human performance include the number of targets, rates of change, visibility, time available, expertise, and display representation. The complete OFM-COG analysis uses the format shown in Table II to describe each subfunction in the OFM. The following examples demonstrate how OFM can be augmented with a description of cognitive tasks and their information-processing resources to identify the consequences of introducing new technology.

III. APPLYING OFM-COG TO ENHANCE MARITIME SAFETY

A. *OFM-COG Identifies the Potential for Technology-Assisted Collisions*

One aspect of vessel navigation that has witnessed dramatic technological advancement is collision avoidance. Radar is an integral element of collision avoidance and development of the

TABLE II
OFM-COG ANALYSIS FOR THE "IDENTIFY TARGET" SUBFUNCTION OF THE OFM

OFM Function/ Sub-function	Cognitive Agent Tasks	Input	Human Information Processing Resources	Output	Task & Environmental Demand
Target Evaluation/Identify Target	IDENTIFY	Potential threat seen on horizon or radar	Long-term memory, Perceptual sensitivity	Narrowed field to monitor	Number of targets, Rates of change
	INTERPRET	Narrowed field to monitor, Rules considered	Long-term memory, Sustained attention	Estimate of target behavior and proximity	Visibility, Time available
	CATEGORIZE	Estimate of target behavior and proximity	Long-term memory, Perceptual sensitivity	Categorized as an immediate threat or not	Expertise, Display representation

TABLE III
THE OFM-COG ANALYSIS OF THE "CONSIDER COURSE CHANGE" SUBFUNCTION OF THE OFM

OFM Function/ Sub-function	Cognitive Agent Tasks	Input	Human Information Processing Resources	Output	Task & Environmental Demand
Target Evaluation/Consider Course Change	INPUT SELECT	Radio, Radar, Visible information concerning target path and intentions	Selective attention, Perceptual sensitivity	Target path information for consideration	Salience of information source, Expertise
	COMPUTE	Target path information for consideration	Processing strategies, Working memory	Potential course changes	Computational aids, Expertise
	INTERPRET	Potential course changes, Rules considered	Long-term memory, Sustained attention	Relative merit of alternatives	Expertise, Display representation
	DECIDE/ SELECT	Relative merit of alternatives	Long-term memory, Processing strategy	Course change required	Expertise, Number of viable alternatives

Automatic Radar Plotting Aid (ARPA) has eliminated many of the tedious, error-prone aspects of radar use. ARPA radars display a wide range of graphic and numeric information, including the relative and absolute speed and direction of any ship within radar range. In addition, ARPA radars can calculate the distance and time of the closest approach, and they provide a variety of trial maneuver functions that can generate a ship's future trajectory given proposed speed and course changes. Some ARPA radars display this information numerically, while others combine it into graphical icons that represent safety zones around the ships. These labor-saving features stand in contrast to traditional radar, which requires operators to calculate this information. With traditional radar, operators must take carefully spaced observations and integrate them using relatively complex geometric calculation procedures.

Fig. 3 shows the OFM of the function "Target Evaluation" and Table III shows the OFM-COG analysis of one subfunction, "Consider Course Change." Shipboard observations were used to identify the subfunctions of "Target Evaluation," and interviews with mariner and training instructors validated the subfunctions and identified commonly used heuristics. For example, in observing several vessel interactions, it was possible to identify the sources of information mariners used as well as the associated physical activities (i.e., radio communication, discussions between crewmembers, and use of radar functions). These observations formed the basis for the initial description of the subfunctions and the triggering conditions, which were validated and expanded with interviews onboard and with training instructors. Table III describes the cognitive tasks and the associated cognitive demands of the subfunction "Consider Course Change." "Input Select" is one critical cognitive task associated with this subfunction; this cognitive task determines what information will be included in the decision-making process, and depends on the information-processing resource of selective attention. Importantly, selective attention is influenced by the salience of the information source and by the expertise of the mariner. The level of expertise will govern how much consideration is given to potentially unreliable information [35]. Inexperienced mariners may be drawn to the salient and seemingly reliable information shown on an ARPA radar. The cognitive task "Compute" describes the process of calculating alternate courses, which can be quite demanding if performed manually. Fortunately, modern radars include trial maneuver functions that show mariners the consequence of various course changes and support less demanding processing strategies. "Interpret" involves a consideration of potential course changes in the context of the rules-of-the-road, which should constrain course selection by limiting the viable options and estimating likely behavior of the target vessel. Some radar designs may undermine this process by encouraging overly simplistic heuristics, such as "maneuver to keep safety zones separated." This heuristic does not consider the rules of the road in interpreting the merit of a potential course. The final cognitive task "Decide/Select" identifies the most promising course change. As in other domains, when the situation is routine and the mariner is experienced, the decision will be based on recognition. Whereas less experienced mariners will rely on a more deliberate evaluation of options [36].

While ARPA radar eliminates many of the error-prone tasks of tracking and avoiding other ships, it may not increase ship safety [5]. In fact, in some circumstances, certain types of ARPA radar may actually promote poor decisions that lead to collisions. Interviews with radar training instructors and analysis using OFM-COG provide specific examples of how the perceptual characteristics of the ARPA radar might lead mariners to misuse it. Specifically, observations of mariners using a training simulator have led instructors to identify aspects of ARPA displays that tend to mislead mariners. The OFM-COG analysis explains and generalizes these findings.

The training simulator involves presenting several mariners, each controlling a separate simulated ship, with a variety of navigation scenarios to give them experience in navigating past each other using actual radar equipment. The simulator provides a relatively realistic representation of how several ships might actually interact. Some scenarios present mariners with situations involving a collision course with another ship while they are near land. In these situations, the safety zones generated by some advanced ARPA's seem to indicate an obvious course change, a deviation to the left that increases the distance to both the land the other ship with a minimum of maneuvering. However, this maneuver violates the rules of the road, which specify a deviation to the right in such circumstances. Because the rules of the road are international standards that govern how ships should respond to each other to avoid collision, it is likely that the other ship will adhere to the rules and deviate to the right, placing the ships back on a collision course. These scenarios often end in a near miss or a collision. Mariners involved in the same scenario who have standard radar seldom violate the rules of the road and deviate to the right. Thus, in some situations, ARPA radars that display safety zones around ships tend to lead mariners to ignore the rules of the road and select course changes that result in collisions and near misses.

An explanation for the errors induced by sophisticated ARPA's lies in the parameters used to generate the safety zone. The safety zones consider only the current speed and direction of the ships, and do not consider information about rules of the road that are likely to influence the course of the other ship. Thus, "safety zones" generated by the ARPA only *partially* specify a safe course. However, mariners occasionally act as if the ARPA display represents the situation *completely*, and in doing so fail to recognize that the rules of the road will govern the future path of other ships and should also govern their course. The safety zones only reveal the physical constraints governing ship interaction (speed and heading) and do not covey intentional constraints (rules of the road). The OFM shows that multiple sources of information must be combined in "Consider Course Change," some of which are not included in the ARPA display. Specifically, Fig. 3 shows four events that should contribute to a course change decision. The ARPA includes only one, so mariners must be trained to attend to information from less salient sources.

In the process control domain, Vicente and Rasmussen [7] have documented similar instances where displays have failed to describe a system completely. They note that operators often act as if the process was physically structured as shown on the display. However, the perceptual characteristics of most displays do not match the characteristics of the underlying process. This can induce poor decision-making because operators fail to consider the properties of the process not represented in the display [7]. This seems to occur with sophisticated ARPA's, where perceptually salient features of the display capture mariners' attention while their conceptual knowledge of the rules of the road goes unused because the display does not contain this information. This analysis indicates a need to augment ARPA displays to provide a more complete representation of the collision avoidance situation. Alternately, this analysis indicates the need to train mariners to use the ARPA as a tool in the context of collision avoidance, rather than as the sole source of information.

B. OFM-COG Identifies Distinct Training Requirements for ARPA Compared to Standard Radar

The previous example shows that while ARPA radar reduces the many elements of the operator's task dramatically, it may generate additional requirements for training and certification. New technology has automated many tasks that require specialized knowledge of complicated procedures; however, proper operation of ARPA radar and interpretation of the data may require even greater amounts of specialized knowledge. Failing to recognize the complexity of ARPA operation and its possible interactions with the fundamental skills of collision avoidance might lead to inadequate certification procedures.

Using the subfunctions identified in the OFM analysis, we generated a series of tables similar to Tables II and III. With this information, we analyzed 40 questions taken from practice tests for the radar observer certification [37]. Each question was independently assigned by the authors to one of the cognitive operations that describe collision avoidance using standard radar [10]. The resulting entries were then compared with the cognitive operations describing collision avoidance with an ARPA.

The results indicated that three general categories of cognitive operations could be identified from the questions:

1) Computing, which involves derivation of quantitative results, based on a straightforward method;

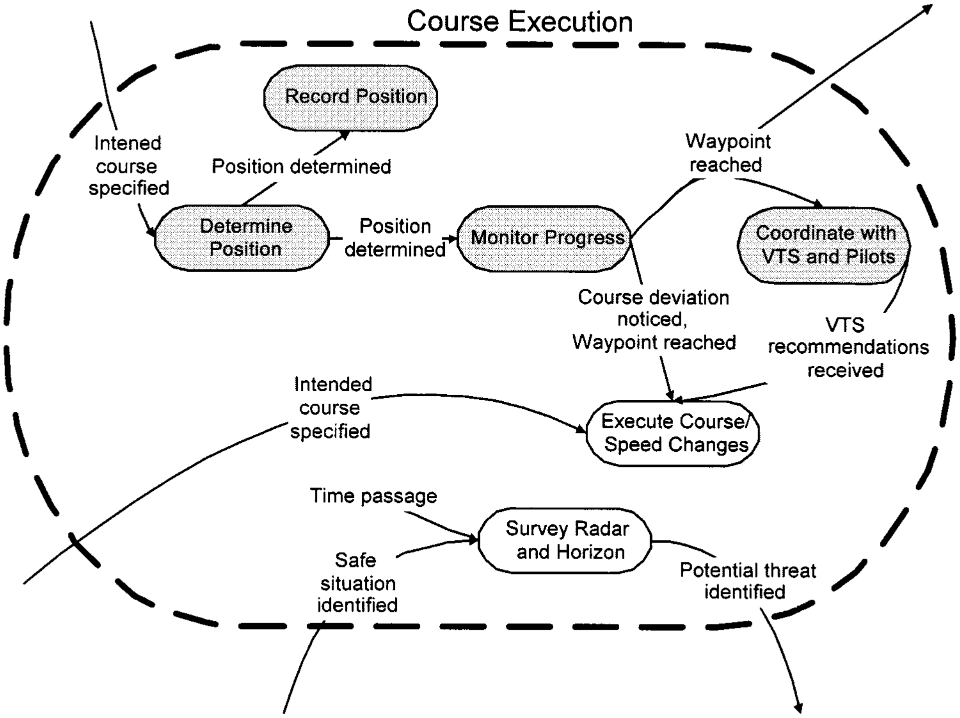

Fig. 4. OFM subfunctions for the "Course Execution" function, with those subfunctions associated with track keeping shaded.

2) Computing and Interpretation, which entails an iterative process of quantitative manipulation and application of the data to an ambiguous situation;
3) Interpretation, which involves application of stored knowledge, such as rules of the road.

An example of a straightforward computing task is one in which the examinee is asked to determine the direction of true motion and speed of a target. Computing and Interpretation is illustrated by questions that are less constrained to specific parameter derivations, such as determining which of a range of potential maneuvers would increase the point of closest approach for all targets. Interpretation might also involve determining target ship orientation based on running light configuration.

The Computing category contained 30 test items, the Computing and Interpretation category four items, and the Interpretation category six items. Comparison of the classification of these exam items with the cognitive operations required by ARPA indicates that the 30 Computing items assess skills that are completely automated with the ARPA. Thus, 75% of the items in a test similar to the USCG Radar Observer examination assess skills that are not required by the new technology. Paradoxically, the capability of ARPA to monitor a greater number of targets enhances the need for interpretive skills such as understanding of the rules of the road and the use of various trial maneuver functions. These are the very skills that are underrepresented on the test. The comparison of ARPA and standard radar shows a major discrepancy between licensing requirements and the operational demands of an ARPA. This in turn demonstrates how OFM-COG can support the detailed analysis needed to ensure licensing requirements keep pace with technological change.

C. OFM-COG Identifies New Failure Modes for Track Keeping with ECDIS Compared to Paper Charts

Track keeping is an important shipboard activity that helps maintain vessel safety. The goals of track keeping are to ensure that the vessel is within an acceptable margin of the intended voyage track, and to determine if course changes are required based on changes in the ship's position, such as reaching a waypoint. The shaded portions in Fig. 4 illustrate the subfunctions involved in track keeping. Currently, track keeping is primarily accomplished with paper charts, but the electronic chart display and information system (ECDIS) and global positioning system (GPS) will radically change track keeping in the coming years. These two technologies are compared using OFM-COG.

Table IV shows the cognitive operations for track keeping with paper charts. The first activity in this table is "Determine position." This activity starts with the cognitive operation of searching and identifying landmarks using charts and the visible environment as guides. The resulting set of potential landmarks is reduced to two or three good points for taking bearing measurements, where "good" points are separated by an angle close to 90° and are easily identified on the paper chart. Mariners code each landmark by reading the bearing from the electronic bearing line on the radar, or the visual bearing, to the selected point. The bearings are coded in written form, and then plotted on the paper chart. "Record position" involves coding bearings, plotting them on the chart, and identifying their resulting vector intersections; the intersections reveal the position of the ship. When the vectors are plotted on the chart, the quality of the position estimate is immediately obvious to the person calculating the vessel position—vectors with extremely acute angles are suspect. In addition, the quality of the estimation is

TABLE IV
OFM-COG ANALYSIS OF TRACK-KEEPING SUBFUNCTIONS WITH PAPER CHARTS

OFM Function/ Sub-function	**Cognitive Agent Tasks**	**Input**	**Human Information Processing Resources**	**Output**	**Task & Environmental Demand**
Course Execution/ Determine position	SEARCH/ IDENTIFY Acquisition	Expected position, Landmarks	Sustained attention, Perceptual sensitivity, Long-term memory	Set of potential landmarks	Chart features, Visibility
	SELECT Interpretation	Set of target potential landmarks	Processing strategy, Long-term memory	Two or three "good" landmarks	Angle between landmarks, Quality of radar return
	IDENTIFY Acquisition	Two or three "good" landmarks	Perceptual sensitivity, Working memory	Bearing of landmarks	
	CODE Handling	Bearing of landmarks	Response precision, Working memory	Written record of bearing	Correspondence between chart landmarks and radar image
	IDENTIFY Acquisition/ Interpret	Previously identified landmarks	Perceptual sensitivity, Working memory	Points to plot on chart	Correspondence between visual/chart landmarks and radar image
Course Execution/ Record position	CODE Handling	Points to plot on chart, Written record of bearing, Time	Response precision	Bearing from landmarks, their intersection revealing position, and present time	
Course Execution/ Monitor progress	TEST Interpretation	Estimated position	Perceptual sensitivity, Working memory	Deviation between actual and planned location, or arrival at a waypoint.	Knowledge of location
Course Execution/ Coordinate with VTS and Pilots	DECIDE/ SELECT Interpretation	Estimated arrival at a waypoint	Long-term memory, Processing strategy	Decision to contact Vessel Tracking Service (VTS) or pilot	The number of other competing activities
	IDENTIFY Acquisition	Conversation with VTS or pilot	Working memory, Perceptual sensitivity	VTS recommendation	Quality of radio contact, Language barriers

available to others who might consult the chart. As each position is plotted, the navigator also extrapolates the current speed and heading to estimate the future position of the vessel. Deviation of a plotted point from the extrapolated estimate indicates an error in course execution, position measurement, or in extrapolation. Monitoring the progress along the track involves comparing the actual position of the ship with the intended position (based on the voyage plan). The track kept on the paper chart provides both a test of current position relative to intended position, and a historical record of location. The manual process of taking bearings and recording positions is easily observed by other crew and includes substantial redundancy, which preserves system performance in the face of inevitable errors. Hutchins [34] provides a detailed description of the robust nature of the traditional track-keeping process.

The data in the column labeled "Task & Environmental Demand" in Table V identify several important failure modes associated with the subfunctions and cognitive tasks involved in track keeping with ECDIS. For example, the subfunction "Determine Position" depends entirely on the quality of the GPS signal and does not include any redundant information sources. In addition to this reduction in redundant-position information, electronic charts also introduce failure modes associated with errors in system configuration and a false sense of position-estimation precision. The initial task of determining position is completely automated by the GPS. The ECDIS can even automatically test actual position against intended track using a feature in which an acceptable error margin can be specified. If the ship deviates beyond this distance, an alarm sounds (provided the feature was engaged and the GPS is functioning normally). Failing to engage this feature could jeopardize ship safety if mariners have come to rely on the automated warning. Also, because any one of several mariners can configure the system, the system configuration and behavior can change in unanticipated ways. The danger of an inappropriate or unanticipated chart

TABLE V
OFM-COG ANALYSIS OF TRACK-KEEPING SUBFUNCTIONS WITH ECDIS

OFM Function/ Sub-function	**Cognitive Agent Tasks**	**Input**	**Human Information Processing Resources**	**Output**	**Task & Environmental Demand**
Course Execution/ Determine position	IDENTIFY Acquisition	GPS	AUTOMATIC	Estimate of current position	Quality of GPS signal
Course Execution/ Record position	CODE Handling	Estimate of current position, Electronic chart	AUTOMATIC	Position plotted on chart, annotated with the current time	Precision of the electronic chart
Course Execution/ Monitor progress	TEST Interpretation	Actual position	Perception, working memory/ AUTO	Deviation between actual and planned location, or reaching a waypoint.	Proper configuration of ECDIS
Course Execution/ Coordinate with VTS and Pilots	DECIDE/ SELECT Interpretation	Estimated arrival at a waypoint	Long-term memory, Processing strategy	Decision to contact Vessel Tracking Service (VTS) or pilot	The number of other competing activities
	IDENTIFY Acquisition	Conversation with (VTS) or pilot	Working memory, Perceptual sensitivity	VTS recommendation	Quality of radio contact, Language barriers

configuration is not a failure mode associated with paper charts.

The tendency to select an inappropriate scale adjustment is another important failure mode associated with electronic charts. With electronic charts, mariners can select a scale that is beyond the precision of the underlying chart data. The precision of paper chart data, on the other hand, is specified by the scale of the chart and cannot be modified. Because the scale of an electronic chart does not share the physical constraints of a paper chart scale, it can be changed over a range that does not necessarily correspond to the precision of the original chart data. The chart data, meanwhile, may not match the precision of the GPS signal, and most electronic charts do not provide an obvious indicator of the precision of chart data. The false sense of precision associated with the electronic chart and GPS data may induce mariners to choose hazardous courses—a failure mode not encountered with paper charts.

Another important failure mode that electronic charts introduce is a reduction in redundant position estimation, resulting in gross position estimation errors. Unless carefully designed, the ECDIS removes the mariner from the process of recording vessel position, meaning that the mariner is given little insight into the factors that might lead to erroneous position estimates. Recording a position on a paper chart superimposes at least two position estimates, one based on extrapolation of the previous position and one based on visual bearings or other position information. These complementary position estimates help identify errors in determining position [34]. Unlike the manual position recording on paper charts, ECDIS shows the quality of the position estimation only indirectly. A numeric measure of GPS signal quality can be selected from a menu, and on some systems it is continuously displayed; however, many mariners have little understanding of the relevance of these numbers. If the signal is lost completely a short alarm is sounded and speed and direction extrapolations (dead reckoning position estimates) are substituted for GPS data. If the initial alarm is missed, the mariner may not notice that the GPS signal is no longer the basis for position estimates. Furthermore, many electronic charts do not maintain a continuous visual record of the vessel track. A track line is shown as long as the same chart or scale is used, but if the scale is changed, the track line is lost. The lack of track line continuity further undermines the ability of mariners to detect a transition from GPS to dead reckoning position estimates. If the mariner does not notice this fundamental shift in the position estimation process, the ship can drift many miles from the intended course while the ECDIS continues to display the position as if the vessel were following the intended course precisely. This is exactly what happened in the grounding of the cruise ship Royal Majesty, where the GPS signal was lost and the position estimation reverted to position extrapolation based on speed and heading (dead reckoning). For over 24 hours, the crew did not notice that the GPS signal had been lost or that the position error had been accumulating. The GPS failure was only noticed when the ship ran aground [38].

Table VI contains a summary of the cognitive analysis results. As the table suggests, ECDIS eliminates much of the work associated with track keeping when performed with paper charts. A reduction of information redundancy accompanies this workload reduction, however. Track keeping with paper charts is based on radar and visual bearing readings (in restricted waters); these are supplemented by position extrapolation (dead reckoning) and by GPS or Loran data. Importantly, track keeping with paper charts is a highly interactive process where multiple estimates of position are compared, reconciled and evaluated [34]. Additional functionality could be added to support redundant information in computation of the vessel

TABLE VI
FREQUENCY COUNT OF THE MARINERS' COGNITIVE TASKS FOR THE TRACK-KEEPING SUBFUNCTIONS

Type of Technology	Data Acquisition	Data Handling	Data Interpretation	Total
Paper Charts	4	2	3	9
ECDIS	1	0	2	3

tracks with ECDIS. However, current ECDIS implementations do not encourage comparison of the multiple position estimates (i.e., GPS, radar bearings, and dead reckoning) that are needed for navigators to integrate the redundant information into their decision making.

From the standpoint of providing visual continuity and encouraging use of multiple data sources to enhance redundancy, the paper chart appears to be superior at this time. Because the ECDIS track line disappears if display manipulations are made, the vessel track is useless for viewing the trend of a deviation from the intended track. Such information may be useful in diagnosing the cause of the deviation, e.g., problems with the autopilot or rudder control.

Although Table VI suggests a dramatic decrease in workload with ECDIS, there are actually a number of low-level tasks *added* that are ECDIS-specific. As such, these were not included in the analysis of subfunctions. Included in these added tasks are the detailed actions associated with evaluating GPS input, chart manipulations (i.e., pan, zoom), and selecting or deselecting display features such as depth markers. The reduced resolution and size of an ECDIS display, compared to a paper chart, makes the simultaneous display of detailed and overview information difficult [39]. Because vessel navigation progresses relatively slowly, the chart manipulations are not likely to overload a well-trained operator. However, some ECDIS configuration tasks may be neglected and features may be used inappropriately. For example, mariners may neglect to turn on critical chart information, such as depth markers. Thus, ECDIS, like other forms of automation, offers potential for enhancing the principal functions of track keeping, but it adds numerous device-specific tasks that undermine workload reductions and open the potential for new navigation errors [40], [41]. More generally, current implementations of ECDIS automate many of the manual tasks of track keeping, but may discourage the use of redundant information and introduce new opportunities for errors. Analysis of track keeping with a paper chart and with ECDIS demonstrates the potential for OFM-COG to identify new failure modes that can emerge with the introduction of new technology.

IV. CONCLUSIONS

We draw three principal conclusions from this research.

1) It is possible to augment OFM to represent the cognitive tasks associated with advanced navigation technology, permitting a comparison of cognitive demands across different levels of automation;
2) the OFM-COG technique is directly applicable to issues related to design, training, and licensing;
3) these promising results suggest that extending OFM-COG would be worthwhile.

As in many other domains, the introduction of new technology on ships substantially changes the role of the human operator and can undermine system performance. OFM provides a promising structure for assessing technological change. OFM describes activities and the conditions that trigger the transitions between activities. It can, for example, clearly identify the activities involved in ship navigation, but it does not specify the cognitive tasks and demands on the mariners' information processing resources. We have augmented OFM with a description of cognitive operations to generate a new approach, OFM-COG. As demonstrated in three examples, OFM-COG supports comparison of the cognitive demands made on mariners by activities described by the OFM. This description provides a valuable means of comparing the consequences of introducing new technology.

The analysis of collision avoidance and track keeping activities shows that OFM-COG can address design, training, and licensing issues associated with the introduction of advanced technology. Error tendencies associated with some ARPA displays suggest that their design could be adjusted to encourage mariners to consider the complete set of factors influencing the collision avoidance situation. Alternately, training should focus on the use of ARPA as a tool in the context of collision avoidance, rather than as the sole source of information. Specifically, training should stress consideration of the rules of the road and guide mariners away from overly simplistic heuristics such as "maneuver to avoid overlapping safety zones." The comparison of ARPA and standard radar shows that OFM-COG supports a detailed analysis that can help ensure licensing requirements keep pace with technological change. Currently, the majority of exam questions fail to acknowledge the role of automation and the increased need for situation assessment skills. The OFM-COG analysis of ECDIS shows that while it automates many of the manual tasks of track keeping, it may disrupt a robust manual process that is less sensitive to sensor failures. The OFM-COG identified three specific failure modes induced by the ECDIS: errors in system configuration, a false sense of position estimation precision, and a reduction in redundant position information. One of these failure modes has received validation in the recent grounding of a cruise ship [38]. Combined, these examples show the broad application of OFM-COG in identifying design, training, and licensing implications of technological change.

Although OFM-COG has proved to be a useful tool in examining maritime navigation, it has several limits that should be considered in future development. OFM-COG does not address personnel allocation. Our analysis concentrated on the cognitive operations inherent in tasks, independently of how these tasks are allocated to crewmembers. Just as OFM has been extended to multi-person situations [42], OFM-COG can be extended to incorporate information on task allocation by linking each discrete task with the crewmember performing it. In our analyzes, the activities are typically performed by one person, with occasional input from another person. Augmenting the OFM-COG to incorporate task allocation would make more complex team activities amenable to OFM-COG analysis, but would require a careful analysis regarding the appropriate unit of analysis. The behavior of some systems cannot be predicted by an analysis of the individuals, but must take a more holistic perspective. A level of analysis that considers the distributed socio-technical system as a whole may be more appropriate than a level of analysis that focuses on the characteristics of an individual [43].

The OFM-COG also pointed to some important interface management issues associated with ECDIS. These issues were not examined in detail because the OFM-COG was constructed at a level of abstraction that did not describe technology-specific activities. Even so, analysis of the cognitive operations and a cursory examination of the potential technology-specific activities revealed important issues associated with chart manipulation and customization. Addressing these issues in detail would require a more detailed OFM-COG. This need points to the critical issue of selecting an appropriate level of system analysis. The needs and goals of the analysis should match the level of detail used in the OFM-COG.

Although OFM describes the rich combination of activity sequences, the tabular representation of cognitive operations suggests that they are performed sequentially. In many instances this is true; however, there are also situations where operations can occur concurrently, or in a nondeterministic order. This is particularly true in the collision avoidance function. If OFM-COG is to provide a timeline of workload demands, this issue must be addressed, which will require adapting the OFM-COG analysis to another form, such as the previously developed computer implementation of OFM. A computer-based implementation provides the flexibility needed to indicate the concurrent, sequential or iterative nature of operator functions. Others have used OFM to develop these types of computer-based models, demonstrating the feasibility of such an approach [16], [44], [45]. There is no conceptual difficulty with incorporating cognitive operations into a computer-based version of OFM. An interesting challenge will be finding a way to use the cognitive demand of ongoing activities to specify nondeterministic activity transitions. Such a feature would help model the complex and important problem of task scheduling and workload management [46], [47].

OFM-COG builds on OFM to identify relevant cognitive constraints that may affect system performance. OFM identifies procedural and situational constraints on acceptable performance and OFM-COG uses that domain specific description to identify relevant cognitive constraints. By bridging the gap between an engineering model of the system and a psychological model of the operator OFM-COG helps identify the cognitive demands of technological innovations. We hope OFM-COG will help others translate psychological considerations into meaningful insights regarding how technology mediates human performance in complex systems.

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