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Critical Assessment of Damage/Fire Control Systems and Technologies for Naval Vessels in Support of Damage Control and Crew Optimization: Risks and Opportunities

Phase IIb: Human Factors Research and the Development of Smart Systems and Decision Aids Related to Damage Control Systems

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Contract Number: W7701-053149/001/HAL

Contract Scientific Authority: Dr. John A. Hiltz, 902-427-3425

Defence R&D Canada – Atlantic

Contract Report

DRDC Atlantic CR 2007-176

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Original signed by Dr. John A. Hiltz

Dr. John A. Hiltz

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Abstract

To develop its next-generation fleet, the Canadian Navy is putting a priority on reducing the through-life costs of its new ships; one of the most promising ways of achieving this is by optimized crewing, which attempts to make appropriate investments in technology that will allow for a reduced crew complement. As damage control is one of the most important manpower drivers for naval platforms, it is a significant area of focus for optimized crewing efforts in the development of the new Canadian Single-Class Surface Combatant. Defence Research & Development Canada Atlantic has realized that though advanced automation, ‘smart’ systems, and decision aids show great promise for a reduction of crew levels in damage control, they can also make the joint human-machine system more susceptible to faults. Consequently, they have requested that a review be performed of human factors research in automation, ‘smart’ systems, and decision aids to help set the direction for the future design or acquisition of advanced automation for damage control.

Résumé

Dans le cadre de la mise sur pied de sa flotte de prochaine génération, la Marine canadienne accorde la priorité à la réduction des coûts du cycle de vie de ses nouveaux navires. L’un des moyens les plus prometteurs d’y parvenir est l’optimisation des équipages, qui se traduit par des investissements appropriés dans les technologies qui permettront d’appliquer cette mesure. Puisque la lutte contre les avaries est l’un des plus importants générateurs de main d’œuvre pour les plates-formes navales, il s’agit là d’un important secteur d’intérêt du point de vue de l’optimisation des équipages dans le cadre de l’élaboration du nouveau navire de combat de classe unique canadien. Recherche et développement pour la défense Canada - Atlantique a compris que bien que l’automatisation de pointe, les systèmes « intelligents » et les aides à la décision laissent entrevoir d’excellentes possibilités de réduction des équipages dans le domaine de la lutte contre les avaries, ils peuvent également rendre le système conjoint homme-machine encore plus sensible aux erreurs. Par conséquent, RDDC Atlantique a demandé que l’on procède à un examen des travaux de recherche sur les facteurs humains dans l’automatisation, les systèmes « intelligents » et les aides à la décision pour aider à orienter la conception et l’acquisition futures de systèmes d’automatisation avancée aux fins de lutte contre les avaries.

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Executive summary

Introduction or Background: To develop its next-generation fleet, the Canadian Navy is putting a priority on reducing the through-life costs of its new ships; one of the most promising ways of achieving this is by optimized crewing, which attempts to make appropriate investments in technology that will allow for a reduced crew complement. As damage control is one of the most important manpower drivers for naval platforms, it is a significant area of focus for optimized crewing efforts in the development of the new Canadian Single-Class Surface Combatant. Defence Research & Development Canada Atlantic has realized that though advanced automation, 'smart' systems, and decision aids show great promise for a reduction of crew levels in damage control, they can also make the joint human-machine system more susceptible to faults. Consequently, they have requested that a review be performed of human factors research in automation, 'smart' systems, and decision aids to help set the direction for the future design or acquisition of advanced automation for damage control.

Results: This review has demonstrated four results: (1) the current trend in battle damage control system design is toward increased and increasingly advanced automation; (2) while this advanced automation shows promise for reducing the crewing requirements for damage control, it will also change the nature of human work; (3) new battle damage control systems are also expected to increase the amount of data that is available to operators as well as the dynamics of information exchange in the damage control organization and across the ship's command team; and (4) the best way to ensure that new battle damage control systems are designed or procured with a proper attention to the relevant human factors considerations is to perform these activities in the context of a structured human factors program.

Significance (including military significance, if any): This review should assist any parties considering the design or acquisition of advanced automation for damage control (or for any other application) in understanding the relevant human factors concerns and in determining the proper course of action to ensure that any automation that is designed or acquired will have the maximum potential of reducing operator workload and increasing operational effectiveness.

Future Plans: Recommendations are given to bolster some elements of this review with further research, and to undertake the effort of developing a human factors process for the design or acquisition of advanced automation for the Canadian Navy.

Torenvliet, G. 2007. Critical Assessment of Damage/Fire Control Systems and Technologies for Naval Vessels in Support of Damage Control and Crew Optimization: Risks and Opportunities: Human Factors Research and the Development of Smart Systems and Decision Aids Related to Damage Control Systems. DRDC Atlantic CR 2007-176. Defence R&D Canada - Atlantic.

Sommaire

Introduction ou contexte : Dans le cadre de la mise sur pied de sa flotte de prochaine génération, la Marine canadienne accorde la priorité à la réduction des coûts du cycle de vie de ses nouveaux navires. L'un des moyens les plus prometteurs d'y parvenir est l'optimisation des équipages, qui se traduit par des investissements appropriés dans les technologies qui permettront d'appliquer cette mesure. Puisque la lutte contre les avaries est l'un des plus importants générateurs de main d'œuvre pour les plates-formes navales, il s'agit là d'un important secteur d'intérêt du point de vue de l'optimisation des équipages dans le cadre de l'élaboration du nouveau navire de combat de classe unique canadien. Recherche et développement pour la défense Canada - Atlantique a compris que bien que l'automatisation de pointe, les systèmes « intelligents » et les aides à la décision laissent entrevoir d'excellentes possibilités de réduction des équipages dans le domaine de la lutte contre les avaries, ils peuvent également rendre le système conjoint homme-machine encore plus sensible aux erreurs. Par conséquent, RDDC Atlantique a demandé que l'on procède à un examen des travaux de recherche sur les facteurs humains dans l'automatisation, les systèmes « intelligents » et les aides à la décision pour aider à orienter la conception et l'acquisition futures de systèmes d'automatisation avancée aux fins de lutte contre les avaries.

Résultats : Quatre observations sont issues de cet examen : 1) L'orientation actuelle de la conception des systèmes de lutte contre les avaries de combat tend vers l'augmentation d'une automatisation de plus en plus perfectionnée; 2) Bien que cette automatisation de pointe laisse entrevoir des possibilités de réduction des besoins en équipage aux fins de lutte contre les avaries, elle changera également la nature du travail de l'homme; 3) On s'attend aussi à ce que les systèmes de lutte contre les avaries de combat augmentent la quantité de données à la disposition des opérateurs ainsi que la dynamique de l'échange de renseignements dans l'organisation de lutte contre les avaries et parmi l'équipe de commandement du navire; 4) La meilleure façon de savoir si de nouveaux systèmes de lutte contre les avaries de combat sont conçus ou acquis tout en accordant l'attention qui convient aux facteurs humains pertinents est d'exercer ces activités dans le cadre d'un programme structuré sur les facteurs humains.

Portée (y compris la portée militaire, s'il y a lieu) : Cet examen devrait aider toute partie envisageant la conception ou l'acquisition de systèmes d'automatisation de pointe aux fins de lutte contre les avaries (ou pour toute autre fin) à comprendre les problèmes liés aux facteurs humains et à déterminer le plan d'action qui convient pour faire en sorte que tout système d'automatisation conçu ou acquis présente le meilleur potentiel de réduction de la charge de travail de l'opérateur et d'augmentation de l'efficacité opérationnelle.

Projets futurs : Il est recommandé d'approfondir certains éléments de cet examen et de prendre l'initiative d'élaborer un processus d'étude des facteurs humains aux fins de la conception ou de l'acquisition de systèmes d'automatisation avancée pour la Marine canadienne.

TORENVLIET, G. *Critical Assessment of Damage/Fire Control Systems and Technologies for Naval Vessels in Support of Damage Control and Crew Optimization: Risks and Opportunities: Human Factors Research and the Development of Smart Systems and Decision Aids Related to Damage Control Systems*, Rapport de contrat 2007-175 de RDDC Atlantique, RDDC Atlantique, 2007.

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1. Introduction

1.1 Background

To develop its next-generation fleet, the Canadian Navy is putting a priority on reducing the through-life costs of its new ships (Hiltz, 2005). This means that when considering the design of a new ship, instead of seeking to minimize acquisition costs, the Canadian Navy is seeking to minimize the sum of the costs related with acquiring and operating the ship, from planning and design through to decommissioning, a holistic perspective on the costs associated with a ship that is being taken by many other navies around the world. Even though the costs associated with the acquisition of a new ship are comparable to its lifetime costs for personnel and maintenance (Taylor, Gallagher, & Marshall, 2003), the number of personnel required to operate and maintain a ship is seen as the most malleable driver of through-life costs (Schank et al., 2005; United States General Accounting Office, 2003). Accordingly, a great deal of attention is currently being paid to optimized crewing efforts which seek to identify appropriate investments in technology that show promise for reducing the number of crew required to operate a ship effectively. Although these investments may increase the acquisition cost of a new ship, any increase should be more than offset by the reductions in the through-life costs related to personnel and maintenance.

As damage control is one of the most important manpower drivers for naval platforms (Schank et al., 2005), it has been a significant area of focus for optimized crewing efforts. Recent technological advances have made it reasonable to conceive of automating significant portions of damage control work in a way that was not possible when the last class of ships acquired by the Canadian Navy, the Halifax-class Coastal Patrol Frigate (**CPF**), was being designed. Consequently, one of the main foci of the optimized crewing efforts currently being undertaken by the Canadian Navy in preparation for the acquisition of future classes of ships such as the Single-Class Surface Combatant is the reduction of the amount of crew required for damage control by the use of advanced automation and related technologies, including smart systems and decision aids.

Defence Research & Development Canada (**DRDC**) Atlantic has realized that although advanced automation, smart systems, and decision aids show great promise for reducing the amount of crew required for damage control, these types of technologies are not a panacea, and if they are poorly conceived they have to potential to actually increase operator workload and make the joint human-machine system more susceptible to faults (Woods, 1996). Notwithstanding these ‘ironies of automation’ (Bainbridge, 1983; Wiener, 1989), automated ‘smart’ systems have tremendous potential for success if their design and/or selection is based on a thorough Human Factors analysis.

1.2 Report objective

The objective of this report is to provide DRDC-Atlantic with a critical review of human factors research related to the design, development, and use of Battle Damage Control Systems (**BDCS**s) that include advanced automation, smart systems, and decision aids. This report will deal with these issues from the perspective of the human-machine interface; a companion report has also been prepared that discusses the technical aspects of advanced fire suppression systems and components.

It should be noted that the purpose of this report is not to review BDCS designs that have been developed by commercial vendors. While such a review could be beneficial, especially in the context of selecting a commercial off-the-shelf BDCS for use by the Canadian Navy, the scope of this report is limited to research efforts whose results are in the public domain. If the Canadian Navy desires to perform such a review in the future, the criteria documented in this report could form a useful input to that effort.

1.3 Method and scope

The results contained in this report were gathered by performing a standard literature review. There were five main sources of data:

1. **Academic journals and conference proceedings.** Since the concerns related to advanced automation, smart systems, and decision aids are multi-faceted, a thorough search of the academic literature was performed by searching a large number of literature databases using the keyword ‘damage control’. The following databases were searched: Ei Engineering Village, Access Science, Aerospace & High Technology Database, Applied Science and Technology, E-journals @ Scholars Portal, Ergonomics Abstracts, IEEEXplore, Inspec, SPIE Digital Library, and the Scientific and Technical Aerospace Reports. Due to the volume of results found and under the assumption that DRDC-Atlantic is most interested in current results, only results from 1995 or later were selected for review.

2. **The Canadian Defence Information Database (CANDID).** CANDID was searched with keywords relating to damage control, automation, and decision aiding/support systems. Again, only more recent results were selected for review.

3. **The Internet and Google™ Scholar.** The internet and Google™ Scholar were also searched with keywords relating to damage control, automation, and decision aiding/support systems. Due to the nature of internet searches, this search was not as structured as the searches listed above, but a reasonable effort was expended to ensure that it was comprehensive and uncovered recent results related to the topic of the review.

4. **Proceedings of the 13th Ship Systems Control Symposium.** One of the most valuable sources of information used in this review, the Proceedings of the 13th Ship Systems Control Symposium, must be treated separately as these proceedings were not found in either of the searches listed above. 31 of the 123 papers presented

at this conference were selected for review based on titles that included references to automation, damage control, or decision-support systems.

5. **Interviews with subject-matter experts.** Two subject-matter experts with research experience in BDCSs were contacted, Dr. Frederick W. Williams of the US Navy's Naval Research Lab, and Mr. André van Erkel of TNO Defence, Security, and Safety, Protection and Survivability of Maritime Platforms division. Interviews with these subject-matter experts were used to learn of the current range of activities performed by their organizations, and to glean pointers into the literature.

In addition to directed searches of the literature, this report also makes use of knowledge of the literature of the general human factors concerns related to advanced automation and decision-support systems already possessed by its author.

It should be noted that the scope of this literature review was constrained by the time available. While this review does cover a wide breadth of issues, it does so at a high-level. This is an appropriate constraint for gaining an understanding of the human factors concerns related with advanced automation and decision-support for BDCSs in general. However, when the results of this report are applied to a specific BDCS design or acquisition, DRDC Atlantic may wish to request additional detail related to specific concerns.

1.4 Report outline

The results contained in this report are presented in six sections. The next section (Section 2) presents an overview of the main points of the report, and the following four sections (Sections 3 through 6) flesh out the five main points uncovered by the review. The report concludes with Section 7, which presents some final conclusions and recommendations.

2. Overview

The results of the literature review that was performed of advanced automation, smart systems, and decision aiding/support systems related to BDCSs have been organized into four main points, as follows:

1. **The current trend in BDCS design is toward increased and increasingly advanced automation.** Since damage control is one of the most important manpower drivers on naval platforms, the damage control community is under pressure to reduce the manning requirements for damage control, and is seeking to do this by an increased reliance on advanced automation. The automation that is being developed is increasingly comprehensive, covering almost all damage control tasks from detecting damage to determining and executing the best strategies for controlling that damage. It is also increasingly 'smart', recognizing damage situations as they evolve, recommending courses of action based on these recognized situations, and even carrying out its recommended courses of action autonomously.

2. **While this advanced automation shows promise for reducing the crewing requirements for damage control, it will also change the nature of human work.** Since much of the automation that has been proposed will off-load tasks related to information gathering and the first response to damage from humans to technology, it seems reasonable to expect that it will be successful in reducing crew requirements. However, in addition to reducing crew requirements, an increased reliance on automation will also change the relationship of humans with the work domain. Where operators formerly had an active role in controlling damage, with advanced automation their role will change to that of a supervisory controller. Human factors research in other domains (including aviation and process control) demonstrates that this change can have subtle, but important, negative impacts. Fortunately, if advanced automation is designed with an understanding of the ways in which it can interact with human performance, many of these negative impacts can be mitigated.

3. **New BDCSs are also expected to increase the amount of data that is available to operators as well as the dynamics of information exchange in the damage control organization and across the ship's command team.** Advances in electronic sensor technology will increase the number and quality of the electronic sensors deployed across a ship. At the individual operator level, there will be challenges related to structuring and visualizing this information in a way that matches known features of human perception and cognition and that effectively communicates the relevant properties of the work domain. Additionally, at the team level, there will be challenges in structuring the information system support so that distributed teams will be able to build and edit a common model of the ship and its current damage control response. While both of these areas represent important challenges for the development of new BDCSs, they are also tremendous opportunities for new BDCSs to not just reduce the number of crew related with

damage control, but also to increase the effectiveness of damage control at the same time.

4. **The best way to ensure that new BDCSs are designed or procured with a proper attention to the relevant human factors considerations is to perform these activities in the context of a structured human factors program.** The human factors considerations related to new, highly automated BDCSs are complex and highly coupled with one another. In addition, since this is such an active area of research and development, it is likely that additional human factors considerations will come to the fore as new technological solutions are explored. For these reasons, it is important that design or procurement activities be informed by a structured human factors program, as is recommended for all military procurements. This will help to ensure that any BDCSs designed by or acquired for the Canadian Navy will have the greatest potential for success at reducing crew levels and also increasing operational effectiveness.

Findings and citations from the literature to support each of these points is presented in the sections that follow.

3. Trends in and affecting BDCS design

3.1 General

The first step in conducting this review of human factors research related to the design, development, and use of BDCSs that include advanced automation, smart systems, and decision aids was to take stock of developments in these technologies in research on or related to BDCSs. The results of this review have been structured as two main sections. The first discusses trends in BDCS research and design in the United States (**US**), the United Kingdom (**UK**), and the Netherlands, and the second discusses broader human-machine interface trends that have been observed in areas related to BDCS design.

3.2 Global trends in BDCS design

3.2.1 The United States

Any review of trends in BDCS design should begin in the US, and specifically, with the US Navy. The US Navy's efforts in optimized crewing are well publicized (e.g., Bost, Mellis, & Dent, 1999; Schank et al., 2005; United States General Accounting Office, 2003; Williams et al., 2003). In addition, since the US Navy is so large and commissions more ships per year than any other navy, it can base new designs on actual operational experience with designs. In contrast, because smaller navies commission fewer ships, they frequently lack operational experience directly related to the design concepts they are exploring and so are more likely to implement relatively untested design concepts.

3.2.1.1 Overall trends

There are a number of important US trends in ship control in general that will likely be felt in the Canadian context and that have an effect on BDCSs:

1. **Advanced automation is implicit in future designs.** Even though a recent overview paper on US Navy trends in the automation of ship controls (McLean, 2003) is from beginning to end about automation, the reader is hard-pressed to find the word 'automation' in the text (it occurs only once, exclusive of references to titles of other reports). In other words, while automation is the broad umbrella under which all development is done, it is so ubiquitous as to not require mention in the details. This informal finding corroborates what was found across the literature: automation is the foundation for all new designs, and on future ships, all human work will occur in the context of highly automated systems.

2. **Automation will move ships toward cross-functional integration.** On older ships that did not have advanced automation and smart systems, functions were not

integrated, but rather were stove-piped. Individual operators were responsible for monitoring system status, sending relevant information up the chain of command, and executing tasks that came down the chain of command. In the context of implicit advanced automation, the US Navy's current goal is to "maximize control system data integration" (McLean, 2003, p. 2). As a first step, this likely means that all information relevant to a given function will be available to a single operator via sensors and data networks, but in the future this could mean that the entire command structure of a ship will no longer be organized around a ship's systems, but instead will be organized around a ship's mission. For damage control in particular, early steps could involve the integration of Integrated Logistics Support with damage control systems (Kuzma, Gorton, O'Mara, Kelleher, & Rhoades, 2003). As ship functions are integrated, first within a function, and then across functions, operators will require different skill-sets than today.[1]

3. **The number of electronic sensors[2] and actuators on ships will increase dramatically.** If ships are to become more highly automated, that automation must be based on electronic means of sensing and affecting the state of the ship. It is important that these sensors and actuators be electronic so that they can deliver data across a network to a remote supervisory controller. Electronic sensor technology is improving in terms of breadth and accuracy of coverage of a ship's systems. In the US, current trends include the use of video to monitor ship spaces (Gottuk, Rose-Pehrsson, & Williams, 2003; Louie, LeBlanc, & Grindstaff, 2003), electronic sensors with embedded logic to more quickly and accurately detect and diagnose fires (Rose-Pehrsson, Hammond, & Williams, 2003), as well as electronic sensors to monitor the states of doors and hatches, fire-main water pressure, and many other ship properties (Downs, Runnerstrom, Farley, & Williams, 2002). Researchers are even considering the development of smart bulkheads with embedded temperature and stress sensors (Kuzma et al., 2003). Just as electronic sensors are multiplying, so are electronic actuators. For example, the DD(X) was planned to include a power system that could self-configure in response to changing loads and damage (Iacovelli, McCullough, & Wadler, 2003) and a great deal of research is being performed into automatic fire-suppression, ventilation control, and fire-main reconfiguration (Williams et al., 2003). Self-configuring power systems remain a very active research topic (e.g., Jayabalan & Fahimi, 2006). As electronic sensors and actuators multiply, operators will become increasingly distanced from directly perceiving the state of a ship, and instead will have to rely on perceptions and actions that are mediated (Vicente & Rasmussen,

[1] This is a significant concern for optimized crewing, as it is expected that the types of personnel that will be capable of controlling functions with advanced automation will also command a higher pay (Schank et al., 2005).

[2] While it may not be a conventional perspective, from a human factors perspective it is important to note that there are at least three classes of sensors. In typical engineering parlance, there are electronic sensors (e.g., a smoke detector), and mechanical sensors (e.g., mercury, and thermocouple based thermometers or the water-level sensor in a toilet tank). Since humans can also directly perceive the data that is sensed by these sensors, humans can also be considered as a class of sensor. Of course, not all classes of sensors are equally applicable (human cannot directly perceive the oil pressure of a generator, but mechanical and electronic sensors can), but they may all be leveraged to solve a design problem.

1990) by technological support.

There is also one final trend that, although it was developed in the context of damage control, is affecting design decisions across the ship:

4. **While all systems will allow for centralized control, the system architecture will allow for distributed operation.** Since warships are intended to travel into areas where they could sustain damage, an increasing trend in ship design is that systems be based on a distributed architecture that is typically controlled centrally. A prime example of this is a new early-warning fire detection system (Rose-Pehrsson et al., 2003) that has integrated electronic sensors and actuators together, and so can detect fires and actuate a water-mist system to control and extinguish fires. Although this system can be monitored and controlled by a centralized damage control console, if the network connecting the two is damaged, this integrated sensor and actuator will still be able to operate. This move toward distributed architectures will affect all areas of ship design (Bost et al., 1999), and should make ships more flexible and robust in the face of damage, as compared to centralized systems which tend to be brittle.

3.2.1.2 Damage control research – DC-ARM

While these trends have been reported at the whole-ship level, they apply equally at the level of damage control operations; indeed, many of the examples cited are specific to damage control. Specific research in damage control that is currently being conducted by the US Naval Research Laboratory is working to flesh these out for the practice of damage control. While there are a number of different projects currently active, the hub of this research seems to be at the Naval Research Laboratory and their Damage Control Automation for Reduced Manning (**DC-ARM**) project. This section briefly discusses some of the important directions of that research, making use of three different reports: Williams et al. (2003), Downs et al. (2002), and Downs (2003).

The DC-ARM project was initiated by the US Office of Naval Research to investigate technologies that could enable a reduction of the crew level required for damage control. The research mandate was quite broad, including concerns from managing the damage control response to the actual fighting of fires and floods. The investigators set an important and ambitious goal for the research products – that they enable a marked reduction in the crew level required for damage control while at the same time containing all damage to the primary damage area (the compartments directly affected by the damage) and increasing knowledge of the event as it progresses. In other words, the goal was not just to reduce manning but to reduce manning while at the same time increasing effectiveness.

Published reports show that the project was largely able to meet its goals. Over the duration of the program, the following technologies were developed:

- an automatic fire suppression system that included advanced electronic sensors (capable of highly accurate early-warning fire detection and characterization) that could control an automatic water-mist fire suppression system;

- an automatically re-configurable fire-main system;
- a ship-wide video system;
- an automatic door closure system; and
- a Supervisory Control System (**SCS**) to allow for operator monitoring and control of the overall system.

Of significant note is the fact that all of these technologies were tested *in situ* on the ex-USS Shadwell under representative peacetime and wartime damage scenarios.

While the overall program is useful for setting context, of more direct relevance to this report is the DC-ARM SCS. While detailed specifications for this system were not located, an overview publication shows that it includes three large-screen displays (at least 60-inch diagonal) and separate data-entry consoles for two of its three operators. The three large displays show a continuously updated status of the damage control relevant properties of the ship (including alarms, map views, and video camera views) while the data entry consoles allow for the entry of verbal reports and communication with other groups. From the SCS, operators can control the fire mains and the water mist system, and they can also monitor and/or override any autonomic responses that may have occurred. The SCS provides information on fire alarms and the sensed characterization of the fire, video surveillance of compartments, and access closure information.

The SCS also provides a suite of decision-aiding functions. These include:

- recommendations on the type of protection that fire attack teams will require based on the predicted growth of a fire and the predicted time it will take to reach the fire;
- recommendations on whether or not manual boundaries are needed in additional to the automatic water mist boundaries based on the predicted growth of the fire, the status of the water-mist system, and the importance of the compartment relative to current operational priorities;
- recommendations of priorities for investigators based on the estimated extent of the damage and the availability of video cameras; and
- recommendation of the best course of action to control the damage at the primary damage area based on the current resources available.

The system is advertised to be able to refine its conclusions and recommendations over time based on the effectiveness of personnel assigned to a given course of action and changes in environmental conditions.

The reports detailing the DC-ARM program, and especially the reports detailing the DC-ARM SCS, stress that the SCS was designed using ‘human engineering’ that included functional analysis, function allocation, and display design considerations (Downs et al., 2002). Unfortunately, the reports do not give details of the specific methodologies that were followed, nor do they interact with any of the human factors guidance that indicates that function allocation for advanced automation does not need to be static (i.e., this function is always performed by the automation and this function is always performed by the operator) but rather that with advanced automation, functions can be allocated to man or machine dynamically, based on conditions (C. A. Miller & Parasuraman, 2003, 2007; Sheridan, 1992). It seems as if the DC-ARM system makes use of dynamic allocation (for example, see the discussion of the distributed versus centralized control of the fire suppression system) but future designs could potentially be improved by a more thorough consideration of developments in this area. This limitation is acknowledged by the researchers involved in the DC-ARM development, when they recommend, "Refinements of the DC-ARM systems should focus on autonomous (local) control of systems and tradeoffs between hierarchical, intermediate, and local controls" (Williams et al., 2003, p. 91). Further, a more forward-looking paper by indicates that a more rigorous consideration of these factors is a direction for future research (Kuzma et al., 2003). It is hoped that these refinements and future research will be done in the context of the human factors literature introduced above.

3.2.1.3 Damage control research – DC-TRAC

In 2002, a team of researchers applied the principles of Naturalistic Decision Making (**NDM**) and Decision-Centered Design (**DCD**) to the design of a damage control personnel management system that they called **DC-TRAC** (Damage Control – Tracking Resources and Crew) (Crandall, Klein, & Hoffman, 2006; T. E. Miller et al., 2002). The requirements for DC-TRAC as well as elements of its design were based on the NDM framework (Klein, 1998), a framework for understanding human decision-making that is gaining increased recognition in human factors circles. It includes a model of human cognition called the Recognition Primed Decision-making (**RPD**) model, and posits that experts do not make decisions according to formal analytical models, but rather that they 'size-up' situations based on their past experiences and act directly, without comparing alternatives. Indeed, when observing experts carrying out their work, it often looks like they are not making decisions at all, but that they just act. Accordingly, requirements gathering under the NDM framework seeks to identify the perceptual cues that experts use to 'size-up' situations, and DCD provides a methodology to design work support around these cues.

The DC-TRAC system is a notable because of the way in which its requirements were generated. While the DC-ARM system had a strong basis in operationally correct requirements, there was no published evidence that those requirements were also based on a recognized model of human cognition. DC-TRAC is an improvement in this regard, because it was based on requirements that were operationally correct *and* that were based on a principled application of the RPD model.

This requirements analysis technique allowed the researchers to develop two main goals for their design activity. First, their analysis showed that damage-control decision-makers need assistance in building and maintain situation awareness. Of first importance is information about the scope of the incident, but a key second ingredient is an understanding of current resource availabilities and locations. Second, their analysis showed that one of the key elements of expertise for damage control decision-making is an in-depth knowledge of the damage control relevant properties of a ship. Here, they focused on creating a tool to help non-experts learn about the potential for cascading faults, and to make rapid decisions.

The researchers also evaluated their design on the ex-USS Shadwell, and found that their design was effective at helping operators to gain an in-depth three-dimensional understanding of damage on the ship. A measure of the effectiveness of this design is that it the concept transitioned into a portion of the DD(X) development.

3.2.2 The United Kingdom

Unfortunately, very little information could be found about directions currently being taken in the UK with respect to damage control and advanced automation. It is likely that the UK Ministry of Defence is performing research in this area as the UK is currently in the process of designing at least two new classes of ship (the Type 45 Destroyer and the CVF Future Carrier) and is pursuing optimized crewing for at least one of these designs (Schank et al., 2005). An overview paper was presented at the 2003 Ship Control Systems Symposium (Parker, 2003), but this paper is written at a high-level and does not present any information beyond what was already covered in Section 3.2.1. A small number of more detailed papers were also presented, but they did not deal directly with damage control concerns.

3.2.3 The Netherlands

3.2.3.1 Overall trends

Due to the pressures of being a small navy and having significant budgetary constraints, the Royal Netherlands Navy (**RNN**) has been pursuing optimized crewing and advanced automation aggressively. The RNN is typically at the forefront of ship automation efforts, and has realized impressive results – the recently commissioned Air Defence Combat Frigate (**ADCF**) requires a base crew complement of 50, down from 227 when the program was started (Schank et al., 2005). While these reductions were not all achieved with automation,[3] the efforts of the RNN at developing and implementing advanced automation are impressive.

A review of the literature shows that the trends that are active in the US (Section 3.2.1.1) are also active with the RNN. Published evidence shows, however, that the RNN is addressing these trends from a more principled human-centred perspective. An overview paper on the RNN's technological directions presented at the 2003 Ship Control Systems Symposium introduces the design challenge as being one of

[3] For example, much of the ADCF's routine maintenance must be done ashore, and instead of having deep expertise on-board, operators can contact a shore-based help-line to diagnose complex problems (Westermeijer, Post, Keijer, & Gillis, 2003).

"attention to the individual operator in a technological [*sic*] complex environment" (Wolff, 2003, p. 1) and concludes that "technology is certainly an important factor in crew reduction, but the emerging insight is that organizational issues … play a more important role" (p. 7).

The RNN seems to have come to this position because they are a few steps ahead of other navies in terms of the saturation of advanced automation and decision aiding technologies. They have hit a wall ("we have come as far as we can go with the present approach" p. 3), and are proposing that to mount this wall they need to move from a highly technology-centred approach to a highly human-centred approach. Of special significance to this review is that damage control is called out as one the difficulties – to reduce crew levels further, the RNN has found that "we will have to reduce the need for human muscle power in damage control" (p. 3).

Some might argue that if the RNN has a frigate with a base crew complement of only 50, they should take stock of their successes as opposed to being concerned that they are at the limit of the possibilities of their past approaches. While this comment has merit, the RNN has this concern because they see that the next pressure will be to improve their operational capabilities. For the RNN, paying attention to the advanced human factors issues will be an enabler for increased cross-functional integration, which in turn will lead to enhanced capabilities and potentially further cost reductions.

3.2.3.2 Damage control research

Wolff's (2003) RNN overview paper set out a direction that it seems damage control researchers in the RNN are already following. The directions in the RNN as of 2003 are as follows:

1. **Decision support.** The ADCF has been designed with a comprehensive decision-support system, which the RNN calls 'advisory functions' (Hagenaars, 2003; Mulder, 2003). These advisory functions present operators with recommendations to support them in the performance of their duties, and span all critical ship operations. In terms of damage control, the advisory functions include boundary cooling management, smoke boundary management, attack and escape routes, smoke removal, stability and bending moments, kill-cards,[4] combustibles plotting and removal, hazardous locations management, casualties plot, nuclear radiation monitoring and management, pre-wetting effectiveness monitoring, detection of malfunctions of systems related to ship survivability, calculation of remaining capacity of fire-main system, ventilation support, and countermeasure support. Some of the advisory functions present actions the operator must take, but in cases where automation exists, the advisory functions can also present advice that it can directly command the automation to execute. In these cases, operators can put the automation in one of three modes: manual mode (where the advice is simply a checklist for operators to follow), confirmed mode (where the operator must confirm each specific action before it is carried out by the automation), and auto mode (where the operator is fully out of the loop, except for a number of high-

[4] Kill-cards are damage control checklists.

criticality decisions for which the operator is kept in the loop).

2. **Distributed control.** The RNN is developing a rich model of distributed control (Janssen & Maris, 2003; Logtmeijer & Westermeijer, 2003; Neef, van Lieburg, von Gosliga, & Gillis, 2003) that allows for critical system responses to be performed automatically, without operator intervention, and even in the absence of a central control system. The important human factors insight here is that as a by-product of developing their model of distributed control, the RNN's researchers are implicitly dealing with issues of function allocation. Not enough details have been published to determine exactly how this problem has been approached, but the RNN could be a good test case of the frameworks developed by Sheridan (1992) and Miller & Parasuraman (2003; 2007).

3. **Event recognition.** The developing model of distributed control described above also involves efforts to apply artificial intelligence techniques to recognize events that are occurring within the ship, and so to deploy automated responses not just on the returns from a small number of sensors, but on a picture that has been compiled from the returns from many sensors. Neef et al. (2003) present a model of system control that involves four levels of mediation between the ship's systems and the operator: a physical platform layer of sensors and actuators, a reactive layer that carries out any necessary high-criticality automatic responses, a diagnosis and planning layer that builds a picture of events as they develop, and an interaction layer that is used by the operator to monitor and control the ship's systems. This type of an approach provides great flexibility for the implementation of adaptive and adaptable operator interfaces (C. A. Miller, Funk, Goldman, Meisner, & Wu, 2005), a topic that will be treated briefly in Section 5.

Contact was also made with a representative from TNO Defence, Security, and Safety (which is, roughly speaking, the Dutch counterpart to DRDC) to discuss how their damage control research was progressing as of early 2007. Current research is still dealing with decision support systems and event recognition, but it is of note that research is now being done in the context of extremely inexpensive heat sensors (about €1 each). Sensors at this price allow for extremely high coverage of ship spaces so that the progress of a fire can be integrated over time and space. This represents a clear opportunity for greater accuracy of diagnosis, but also a potential for operator overloading. A second area of research continues to develop ideas on distributed control and automatic system reconfiguration. Finally, a third line of research is working to develop better damage control displays that more accurately present information on the status of the ship to operators (A. van Erkel, personal communication, 15 March 2007).

3.3 Human-machine interface trends in areas related to BDCS design

3.3.1 General

While the review of global trends in BDCS design (Section 3.2, above) demonstrated directions that are being followed in research closely related to BDCSs, there are also a number of broader research areas that may be relevant to BDCS design. Three of these areas are presented below.

3.3.2 Emergency response systems

Note: *Although it was not originally planned to include emergency response systems in this review, the March 2007 issue of the* Communications of the ACM *(Vol. 50, No. 3) was a special issue on these systems, and included two articles that are germane to a consideration of advanced automation and decision aiding systems for damage control. This review is limited to a consideration of these two articles, and so may not correctly represent the state of the art in this domain.*

Emergency response systems are systems that have been designed to facilitate an organized response to some large calamity, such as 2005's Hurricane Katrina. Although emergency response systems typically operate over longer time periods than a ship's damage control organization (days versus hours), there are many important similarities between the two types of work:

- **Both types of work involve a high degree of uncertainty.** Damage control organizations and emergency response organizations are most important in times of high uncertainty. During these times, the accurate communication of facts, decisions, and the intent behind those decisions is crucial in helping operators to manage uncertainty.

- **Both types of work involve a high degree of stress and emotion.** Since operators in emergency response and damage control are typically working under an elevated level of stress and emotion, their capacity for accuracy in communication or comprehension may be degraded. In other words, elevated stress and emotion degrade operators' abilities to cope with uncertainty.

- **Unanticipated incidents are a way of life.** Just as it is widely acknowledged that actual naval damage control incidents are almost always unique, so broader emergencies also never seem to go according to plan. In this type of work context, operators must be given tools that allow them improvise to fill in the gaps between the various plans (or procedures) that they may have been trained in.

A recent issue of the *Communications of the ACM* included two articles providing an overview of some of the current issues in the design of emergency response systems. The first of these articles (Carver & Turoff, 2007) discusses at a high level the human factors considerations for ensuring that emergency responders are provided with information support that helps them to make good decisions in the face of uncertain information. The authors spend some time discussing the psychological factors at play for emergency response organizers, including:

- a complete focus on the problem that ignores all that is not relevant;
- necessary improvisation using potentially unorthodox ways to make sense from information and come to decisions; and
- a sense of challenge and motivation due to the critical nature of the problem; but
- a potential to fall prey to "threat-rigidity syndrome" in which decision makers freeze and resort to a potentially inappropriate set of well-learned rules and fixed plans.

The authors propose that technological support for emergency responders should explicitly reckon with these psychological factors, and so work support should be provided that:

- supports operators in their desire to focus on the problem at hand by ensuring a minimum of effort to carry out the required tasks (i.e., the work support does not get in the way);
- includes methods of broadening or shifting operators' focus as necessary; and
- allows for creativity by providing operators with the information required to work outside of established plans and procedures.

While the article includes many recommendations for achieving this goal, the most germane in the context of this report is a framework that outlines the appropriate human-factors contributions for all of the different types of work support required by emergency response teams. This framework has been included as Figure 1, below.

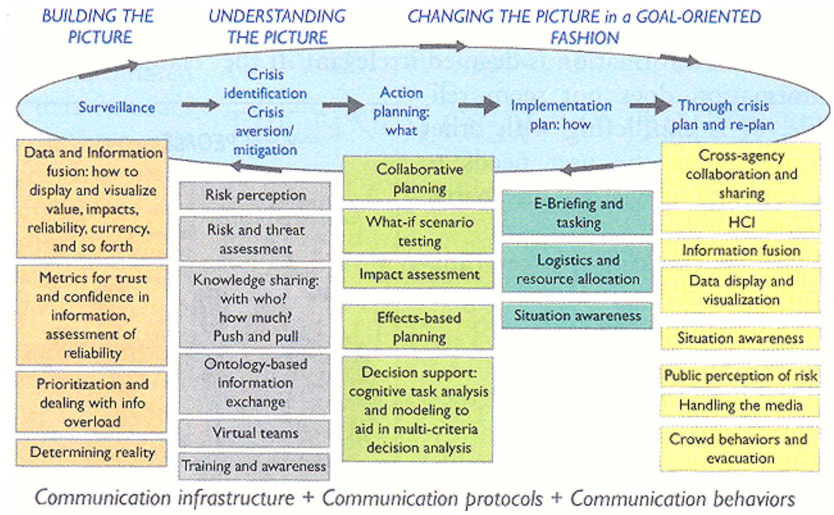

Figure 1. *Framework for human factors efforts over the scope of work support required by emergency response teams (reproduced from* Communications of the ACM, *March 2007, Vol 50, No. 3, p. 35).*

The second article (French & Turoff, 2007) gives a brief overview of some of the high-level issues related to providing decision support systems for emergency responders. While the article is short, it provides three important guidelines that should be taken into account in the development of decision support systems for damage control. First, decision support systems need to be well-tailored so that they can be readily embedded in the prevailing culture where the decisions are to be made. Second, the data for input to decision support systems is rarely clean and error free. Accordingly, the quality of data should be assessed by cross checks, and operators should be made aware of conflicting data. Third, if organizations are to learn from emergencies they have experienced, decision support systems should be built with a capability to record the necessary information for a post-incident audit. For damage control, an audit system could also allow for more effective training, as instructors could review the records of the ways in which the work support was used. It is also possible that audits could reveal problems with the decision support that could be resolved in future system updates.

3.3.3 Decision support systems in general

Performing a comprehensive review of the human factors concerns in the design of decision support systems is beyond the scope of this review. Instead, this section is limited to briefly reviewing a small number of decision support systems that have been designed for military or maritime applications, and summarizing some of the most important human factors issues raised by these examples. Note that this section is not concerned with the technical aspects of the decision support systems (such as knowledge representation or reasoning structures) but more broadly on the way in which the requirements for decision support systems should be generated.

One of the best examples of a decision support system in a military context is the one that was developed as a part of the Tactical Decision Making Under Stress (**TADMUS**) program to support officers in the Combat Information Center of a warship. Work in this program uncovered two important insights for the development of decision aids for damage control:

- **Psychological relevance.** Early generations of decision support systems were based on formal models of analytical decision making, and attempted to assist operators in comparing decision alternatives and selecting the best possible alternative. However, researchers in the TADMUS program found that it was much more useful to base a decision support system on models of cognition like the RPD model, than to use formal decision making models whose psychological relevance was questionable (Kelly, Morrison, & Hutchins, 1996). Just as with the DC-TRAC program (see Section 3.2.1.3), these researchers found that it is useful to base the requirements for a decision support system on an understanding of the cues that experts use to recognize and act on a situation, and then to design the decision support to make those cues more salient.

- **Display form.** Research has shown that human perception is facilitated by appropriate graphical presentations (Vicente & Rasmussen, 1992) because these types of presentations reduce the amount of effort and time required to perceive and act on information. Although the TADMUS decision support design included textual elements, researchers found that it was beneficial to present the most important decision cues graphically (Hutchins, Morrison, & Kelly, 1996).

A detailed technical report on the TADMUS decision support system has also been published (Hutchins, 1996), and provides a detailed rationale for the requirements gathering process and the human factors elements of the system design. This report could be useful in the context of planning the human factors activities required in the design of decision support for damage control.

Bryant, Webb, & McCann (2003) have interacted with some of the conclusions of the TADMUS program, and argue that a strict reliance on the RPD model may not be appropriate. They contend that the choice of decision-making strategy (and hence, the type of decision support that operators should be offered) is likely based on the amount of time and resources available. In situations where operators have a great deal of time and resources, decisions tend to benefit from the in-depth assessment of the analytical approach, but in situations where time and resources are constrained they tend to act on intuition. However, since damage control decisions tend to made in situations that are time and resource constrained, it is probable that the NDM approach generally more relevant than a more analytical approach.

While many decision support systems have been designed for a wide variety of applications, outside of the decision support systems already reported on in Section 3.2, only two other decision support systems could be found for military, naval, or maritime applications. One was designed to provide support for submarine survivability (D. Lee, Lee, & Lee, 2002) and the other to support decision making related to flooding on passenger ships (Ölçer & Majumder, 2006). However, since published reports of both of these systems do not include insights relevant to a human factors review, they were not reviewed in-depth.

3.3.4 Augmented cognition and adaptive interfaces

Augmented cognition is a nascent field of human factors research that aims to improve human performance in high-workload environments by the development of work support, and especially adaptive interfaces, that automatically adapt to operators based on physiological measures of operator state (Schmorrow & Kruse, 2004). While this stream of research shows promise for systems requiring continuous real-time control of fast-moving systems (e.g., aircraft, uninhabited aerial vehicles, etc.) it is not likely that damage control systems would be a useful test-bed for this research, at least in the near future. Augmented cognition research has not yet focused on the support of teamwork, whereas damage control operators involve many different teams and sub-teams. While a critical review of augmented cognition research in relation to damage control might yield some useful results, the author is sympathetic with Miller et al. (2005) who recommend that operator-adaptable interfaces are currently to be preferred over adaptive interfaces.

4. The impact of automation on human work[5]

4.1 General

A major aim of this review is to ensure that any advanced automation, smart systems, and decision aids employed in future damage control systems designed for or procured by the Canadian Navy achieve optimized crewing objectives while capitalizing on human capabilities and respecting human limitations. Over the past two decades, a growing literature has drawn attention to the potential drawbacks of human-automation interaction. This literature is relevant not only to advanced automation, but also to smart systems and decision aids, because in human factors terms, these three items are all just different approaches to automation.

J. D. Lee (2006) has recently compiled a comprehensive review of the issues that have been raised in the literature, and this section presents a summary of his findings.

4.2 Out-of-the-loop unfamiliarity

Control engineers often think about automation in the context of feedback control loops. In that context, automation replaces control loops that include a human element with ones that do not. The effect of this is either to remove the human from the control model altogether, or more frequently to assign the human to supervisory control loops – away from the data, decision, and doing frontier. Once outside the inner control loops, human operators find it very difficult to remain in tune with what the automation is doing. Several aspects of automation design contribute to this problem. First, automation systems frequently fail to provide the human supervisor with adequate feedback (that is, information) about the behaviour of inner control loops. Second, the human operator is not well-suited to the passive monitoring task, even when provided with adequate feedback. Third, supervisory control encourages task switching and interruptions which further remove the operator from the inner control loops. Finally, since operators are out-of-the-loop, they tend to develop poor mental models of inner control loops and the processes that they control.

All four of these design factors are likely to contribute to human-automation challenges in damage control.[6] The first aspect, removal of the human from inner

[5] Dr. Greg A. Jamieson of the University of Toronto is to be thanked for his substantial contributions to this section.
[6] It is important to note that the assertions to follow are necessarily predictive – the damage control automation does not yet exist. It would be deceptively easy for any automation designer to dismiss these predictions. Engineers are, in fact, adept problem solvers and, once made aware of any specific issue, can posit viable solutions to them The key here is that the predictions are a projection of *persistent observations of difficulties encountered when humans interact with advanced automation*. It is the aim of this research to circumvent these design shortcomings through informed analysis and design.

control loops, is likely a necessary design decision if reduced workload (or reduced manning) is to be achieved. The design challenge is to provide access to inner control loops without overloading the operator – a very difficult balance to strike. The second and third aspects remind us that the operator is likely to have an incomplete awareness of the automation state and behaviour. The final aspect of automation design that contributes to out-of-the-loop unfamiliarity, poor mental models, can be viewed as a consequence of the above and a precursor to inappropriate reliance decisions (see Section 4.5, below).

4.3 Clumsy automation

Automation is frequently targeted at high-tempo phases of work with the aim of reducing operator workload (see Section 4.2, above). Ironically, if the human-automation interaction is not well anticipated, this can result in an increase in workload at times when the human is already busy. This phenomenon is called 'clumsy automation'; clumsy automation can be further subdivided into non-routine or routine clumsiness. Non-routine clumsiness is associated with non-routine events in the domain. This could include maintenance evolutions or emergency operations. Routine clumsiness is manifested during routinely occurring high workload phases of operations, such as start-up or shutdown of major systems. For example, flight management systems are notorious for forcing pilots to perform data entry tasks during busy pre-flight evolutions.

Damage control seems highly susceptible to non-routine clumsy automation. The highly temporal nature of the domain suggests that the most critical automation tasks will be performed when the operator is extremely busy and under extraordinary duress. What might be anticipated as necessary and simple human inputs to the automation could quickly become overwhelming annoyances.

Damage control automation may also be susceptible to routine clumsiness, but to a much lesser extent compared to non-routine clumsiness. In the damage control domain, set-up may be necessary when a ship makes ready to sail or when maintenance activities cause temporary changes in the resources or constraints of the damage control system.

4.4 Automation-induced errors

Even well-design automation introduces new opportunities for humans to make errors, and the occurrence of those errors and their effects can be difficult to predict or detect. There are three types of errors that are commonly acknowledged to be induced by automation:

1. **Mode errors.** Mode errors occur when mode status or transitions are not effectively communicated to operators. Operator actions that are reasonable in one mode may have dramatically different effects in another mode.

2. **Brittle failures.** Brittle failures occur when simple data entry slips result in sudden

and severe degradation in system performance. Opportunities for such failures are afforded by highly automated decision processes that are susceptible to poor quality data.

3. **Configuration errors.** Configuration errors occur in the set-up phase of automation, particularly if data entries are not rigorously checked.

Of these three types of errors, mode errors are the most insidious and the most widely discussed in the human factors literature. Designers use modes to increase the context sensitivity of the automation. Although the approach is powerful and flexible, human operators engaged in supervisory control experience a great deal of difficulty keeping in sync with the automation modes, particularly when those modes are poorly enunciated or when transitions are induced by internal logic that is not well understood by the human.

Brittle failures and configuration errors, while important, appear to be more idiosyncratic. Both can be thwarted by rigorous input checking – an accepted practice in software engineering. It is not expected that these types of errors will be a large factor in the context of the present study.

4.5 Inappropriate trust

Trust is a complex attitude held by a person towards other agents (including automated ones) that may help or hinder achievement of the person’s goals. Because this attitude develops implicitly and in response to a wide variety of influences, it is extremely difficult to model. However, there is substantial empirical evidence that trust affects reliance on automation. Inappropriate reliance behaviour can take the form of misuse (relying on automation that is incapable) or disuse (rejecting capable automation). Since people tend to rely on trusted automation and reject distrusted automation, it is easy to anticipate how trust plays a substantial role in reliance decisions and the appropriateness of those decisions.

4.6 Behavioural adaptation

Operators and organizations often adapt their behaviours in ways that nullify the safety or performance advantages of automation. This adaptation is usually implicit and may take one of two forms. First, operators sometimes respond to increases in safety with more risky behaviour; as if a risk set-point exists for the system as a whole. Second, organizations may suffer a ‘diffusion of responsibility’ amongst themselves. This can create situations in which no one is explicitly responsible for critiquing the decisions and actions of the automation.

These types of behavioural adaptation are not expected to be a major issue for damage control automation. The maladaptive behaviour of adopting more risky behaviour is most commonly encountered in familiar tasks that are aided by automation. For example, anti-lock braking systems do not improve driving safety because drivers adapt by traveling at higher speeds and braking more aggressively. Damage control automation is unlikely to replace tasks that are so highly practiced, so this maladaptive behaviour seems unlikely. Diffusion of responsibility also seems an unlikely problem for damage control automation because military organizations are highly practiced at role allocation and reinforcement. One would expect this organizational strength to carry over to mixed initiative damage control teams.

4.7 Skill loss and skill shift

Workers often suffer degradation in their manual task performance skills when those skills are not regularly practiced (as is the case when the skill-based tasks are automated). These tasks are often associated with physical control tasks, but degradation of cognitive tasks has also been noted. In situations where automation assumes only a portion of the tasks associated with a job, it may have the effect of shifting emphasis to other skills. If these skills are less robust in the operator population, the joint human-automation system may suffer performance degradations from the introduction of automation.

4.8 Job satisfaction

Although automation is often envisaged by designers as relieving workers of some burden, it often has the unintended effect of reducing worker satisfaction with their job. This is often explained as a combined reduction in decision latitude and increase in work demands. While automation may reduce workload, it also reduces an operator's ability to affect the work system, resulting in a reduced sense of control. Meanwhile, the operator remains in charge of a more powerful and capable system; one that requires him to exercise less robust skills at a pace determined by a machine. The result can be highly demoralizing for the worker.

4.9 Implications

The challenges involved in human-automation interaction introduced in this section could be some of the most difficult to overcome when designing or procuring a new damage control system. Unfortunately, it is deceptively easy for automation engineers to dismiss them. Engineers are adept problems solvers, and once made aware of specific issues, can posit viable solutions to them. The key is, however, that *these issues are persistent observations of difficulties encountered when humans interact with advanced automation*. No silver-bullet solutions have presented themselves, other than acknowledging these issues during early design phases, testing all design decisions against them, and then re-testing with operators in representative settings (see Section 6 for more details).

If such an approach is followed, the list below enumerates some of the specific implications of this review on advanced automation for damage control:

- **Out-of-the-loop unfamiliarity.** This is one of the most significant challenges for damage control automation. If it is true that damage control operations frequently involve improvised responses (see Section 3.3.2) that go beyond the planned applications of a damage control system, operators' ability to improvise novel damage control responses in the face of unanticipated situations will be reduced the less conversant they are with the damage control properties of the ship.

- **Clumsy automation.** This could be a significant concern for damage control, especially if the damage control system requires cumbersome interaction methods right at the time that operators' workload is high. Fortunately, the risk of this issue can be reduced through a rigorous human factors design or procurement program (see Section 6).

- **Automation induced errors.** While it is not possible to predict precisely where mode errors will be a problem in damage control, if an automated system has modes, they can pose problems. Designers of new systems or evaluators of systems being procured must be vigilant to consider how mode errors could happen and what their impact would be.

- **Inappropriate trust.** In the context of a system with potentially thousands of sensors, inappropriate trust will be a significant issue. For example, Rose-Pehrsson et al. (2003) report that their early-warning fire detection system improves on conventional systems as it has an accuracy rate of 80%. If this sensor is implemented and operators are not aware of the 20% probability of false alarms when considering an alarm in a single space, inappropriate trust will be a significant issue. While sensor redundancy mitigates this issue somewhat, since no electronic sensors will be 100% reliable, inappropriate trust will also be a persistent issue.

In the context of damage control on a naval platform, the issues of behavioural adaptation, skill loss and skill shift, and job satisfaction are not expected to be significant.

5. Additional human factors considerations

5.1 General

So far, this report has documented the broad trends that are currently active in the design of BDCSs and in areas related to BDCS design, and has summarized the way in which the main trend – that of increasing automation – can have an impact on human work. Two of the remaining trends reported in Section 3.2 have not yet been dealt with as explicitly as the first trend. The concerns of these trends are best posed as two questions, which this section will attempt to answer. First, if the number of electronic sensors and actuators will increase dramatically, what human factors advice can be given to help operators deal with this increase? Second, what insights are currently in the human factors literature to assist in moving toward cross-functional integration?

These questions are actually tightly coupled with one another. On the one hand, it is increases in the number of electronic sensors and actuators that deliver the data that allows for cross-functional integration. On the other hand, operators who are in charge of integrated functions by definition must deal with more data than operators in charge of a single function. Considered together, these questions can to be answered with broad guidance from the human factors literature about the techniques that should be applied across the design life-cycle, from requirements gathering through to detailed design.

5.2 Techniques for requirements gathering

The major challenge for damage control is to find a method for requirements gathering that is able to cope with the challenges and complexities of damage control, but that is also able to generate concrete design guidance. Since one of the overriding aims of current design and development efforts in damage control is to reduce manning, methods of analysis that are based on the ways that work is currently done (such as Hierarchical Task Analysis (Annett, 2003) or traditional MIL-HDBK-46855A Mission, Function, and Task Analysis) are not well-suited to the early and foundational requirements gathering stages of a project. They are suitable for later stages of design, or for incremental improvements to existing designs, but they carry with them too many assumptions about the way work is done today to allow for revolutionary changes in the way that work is done.

Perhaps the most promising framework for requirements gathering for damage control is Cognitive Work Analysis (Vicente, 1999). Cognitive Work Analysis is a broad framework for understanding human work in complex socio-technical systems, and was designed to support the development of work support for domains that suffer from unanticipated faults, the class of calamities that were not foreseen by system designers. The framework covers requirements analysis at many different levels, from the early conceptual phases of design through to the design of team and reporting structures (although the latter phases of analysis are not as well-developed as the early phases).

In addition, early phases of the analysis are consciously operator-independent, so the techniques of Cognitive Work Analysis lend themselves well to design for optimized crewing. One of the techniques of Cognitive Work Analysis, called Work Domain Analysis, has already been successfully applied to damage control on the CPF with the express intent of ensuring that results will generalize to design for the Single-Class Surface Combatant (Torenvliet, Jamieson, & Chow, in review; Torenvliet, Jamieson, & Cournoyer, 2006).

As has already been argued in this report, techniques from the NDM community also show great promise for the design of work support for damage control. These techniques have been applied hundreds of times over the past 20 years, so that now a set of techniques has arisen under the name 'Cognitive Task Analysis' (Crandall et al., 2006). Cognitive Task Analysis can be used as a standalone technique, or it can be integrated into the Cognitive Work Analysis framework.

Both Cognitive Work Analysis and Cognitive Task Analysis are currently being applied in domains to assist in the development of 'smart' work support to help operators cope with advanced automation and a dramatic increase in the amount of data they must consume. Consequently, they both show good promise for continued application to damage control.

5.3 Techniques for detailed design

A typical complaint about many human factors analyses is that while they are good at informing design, they do not directly lead to designs (Linegang & Lintern, 2003). One of the benefits of the Cognitive Work Analysis framework introduced above is that it includes a specific design methodology, called Ecological Interface Design (Burns & Hajdukiewicz, 2004), that has been designed to use as inputs the outputs from the various phases of Cognitive Work Analysis. One of the foundations of Ecological Interface Design is the use of data visualizations that match operators' perceptual processes, and so the technique includes guidelines for building effective visualizations.

Beyond techniques like Ecological Interface Design, there is a great deal of human factors research into the types of information visualizations that are most efficient for human perception (e.g., Ware, 2004) and interaction techniques to assist operators in solving complex problems (e.g., Mirel, 2004). In addition, if damage control functions are going to be increasingly integrated, operators may have to switch from knowing everything related to their job about the ship to knowing *how to access* everything related to their job about the ship. Accordingly, operators may have to interact with large and virtual information spaces. If this happens, the techniques of the field of Information Architecture (Morville & Rosenfeld, 2007) will become increasingly relevant, as this field is concerned with structuring information for access and comprehension.

Of course, wherever detailed design techniques are used, design processes will benefit greatly from the continuous development of human factors prototypes to embody emerging design concepts (Arnowitz, Arent, & Berger, 2007; Snyder, 2003) and the continuous application of usability testing (Rubin, 1994) to ensure that the designs are informed by the experiences of real operators, not just the design team. It should be noted that all of the techniques referenced in this paragraph were originally developed in the context of the development of consumer software applications, and so present rapid and cost effective techniques that focus on results. More rigorous testing in a simulated environment should be performed (indeed, DC-ARM researchers recommend three phases of testing, including simulator-based testing, testing on an active ship, and weapons effect testing on the vulnerability of systems (Downs et al., 2002)), but performing these 'cheap and dirty' tests during the design phase can de-risk the final acceptance testing significantly.

6. Human factors processes in support of design and procurement

While the preceding sections of this report have covered a large number of topics, the most significant weakness of the data presented so far is that it is not well structured for use in a program to design or acquire new damage control systems for optimized crewing. Especially Sections 3 and 4 can make the human factors considerations involved in the design of automation, ‘smart’ systems, and decision support for damage control read like a checklist of issues that each need to be addressed in turn. While these issues do need to be addressed systematically, it is actually not possible to compile a full list of all of the human factors considerations of any design problem in advance of actually performing the design. First of all, knowledge about the use of advanced automation, ‘smart’ systems, and decision support is continually expanding, and new issues are always being uncovered. Second, most of the issues raised in this report are either coupled with one another, or manifest themselves in different (and potentially unexpected) ways across designs. Third, it is possible that design or acquisition activities for the Single-Class Surface Combatant will raise new issues that would not be experienced in any other context. For this reason, it is important that these human factors considerations be dealt with as a part of structured human factors process, either for design or acquisition.

The Canadian Forces have typically relied on human factors processes for design or acquisition as per MIL-HDBK-46855A. While this process has served past acquisitions quite well, it does not currently interact with newer requirements gathering techniques (like Cognitive Work Analysis or Cognitive Task Analysis), and it is based on a military design standard (MIL-STD-1472F) that has not yet been revised to include the human-performance issues of advanced automation. Consequently, MIL-HDBK-46855A is somewhat weak in terms of the design or acquisition of advanced automation for damage control.

It is possible that to establish a process for design or acquisition, DRDC should look beyond current military processes and instead investigate acquisition processes in the Nuclear and Process Control industries. These industries have similar acquisition concerns as the military, and have done a great deal of effort to come to terms with the realities of the human-performance implications of advanced automation.

No matter what process is chosen, an important closing note for this report is that consideration of all of the human-factors issues related to advanced automation, ‘smart’ systems, and decision support systems is best done in the context of a rigorous human factors process.

7. Conclusions and recommendations

7.1 Conclusions

This critical review of human factors research related to the development of advanced automation, 'smart' systems, and decision support systems related to BDCSs has made four arguments. In brief:

1. **The current trend in BDCS design is toward increased and increasingly advanced automation.** This argument was substantiated by reviewing trends in BDCS development in the US and the Netherlands, as well as by reviewing trends in a number of areas related to the design of BDCSs.

2. **While this advanced automation shows promise for reducing the crewing requirements for damage control, it will also change the nature of human work.** This point was substantiated by presenting a summary of the ways in which advanced automation has been observed to affect human work.

3. **New BDCSs are also expected to increase the amount of data that is available to operators as well as the dynamics of information exchange in the damage control organization and across the ship's command team.** To help cope with these changes, the literature on human factors approaches to requirements gathering and detailed design was briefly reviewed. The frameworks and techniques reviewed should help to ensure that new BDCSs are able to achieve the goal of reducing crewing requirements for damage control while at the same time increasing the effectiveness of the damage control organization.

4. **The best way to ensure that new BDCSs are designed or procured with a proper attention to the relevant human factors considerations is to perform these activities in the context of a structured human factors program.** While the development of a human factors program for the acquisition or design of advanced automation for damage control is beyond the scope of this report, this section concluded that such a process is necessary, and that DRDC-Atlantic would be well-served by investigating the processes used by other industries to design or acquire advanced automation.

7.2 Recommendations

The following recommendations indicate lines of research that could be followed to address the limitations of this review, bolster its findings, or make overall contributions to the effort to reduce the crew levels required for the Single-Class Surface combatant by the application of advanced automation.

1. **Damage control research and development in the UK.** The most significant limitation of this review is that it was unable to learn much about damage control

research and development in the UK. As the UK is currently in the midst of the development of two new classes of ships, such a review might be beneficial in terms of better understanding the state of the art in damage control automation.

2. **Augmented cognition.** While the author is sceptical about the contributions that the Augmented Cognition community can make to the design of advanced automation for damage control, it may be beneficial to perform a structured review of the research performed by this community to see if such scepticism is justified.

3. **Detailed design review.** This review was not able to uncover many items related to the detailed design of the various damage control interface concepts reviewed. It could be beneficial to conduct visits with the relevant military research agencies in the US, the UK, and the Netherlands to gain a detailed view of their respective damage control human factors programs.

4. **Development of a human factors process.** In the light of the results presented that the current MIL-HDBK-46855 human factors process may not be adequate for the design or acquisition of advanced automation for damage control, DRDC-Atlantic should investigate developing a new process (or a modified version of MIL-HDBK-46855) based on findings from the Nuclear and Process Control industries.

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List of symbols/abbreviations/acronyms/initialisms

ADCF	Air Defence Combat Frigate
BDCS	Battle Damage Control System
CANDID	Canadian Defence Information Database
CPF	(Halifax-class) Coastal Patrol Frigate
DC-ARM	Damage Control Automation for Reduced Manning
DCD	Decision-Centered Design
DC-TRAC	Damage Control – Tracking Resources and Crew
DRDC	Defence Research & Development Canada
NDM	Naturalistic Decision Making
RNN	Royal Netherlands Navy
RPD	Recognition Primed Decision-making (model)
SCS	(DC-ARM) Supervisory Control System
TADMUS	Tactical Decision Making Under Stress
UK	United Kingdom
US	United States

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To develop its next-generation fleet, the Canadian Navy is putting a priority on reducing the through-life costs of its new ships; one of the most promising ways of achieving this is by optimized crewing, which attempts to make appropriate investments in technology that will allow for a reduced crew complement. As damage control is one of the most important manpower drivers for naval platforms, it is a significant area of focus for optimized crewing efforts in the development of the new Canadian Single-Class Surface Combatant. Defence Research & Development Canada Atlantic has realized that though advanced automation, 'smart' systems, and decision aids show great promise for a reduction of crew levels in damage control, they can also make the joint human-machine system more susceptible to faults. Consequently, they have requested that a review be performed of human factors research in automation, 'smart' systems, and decision aids to help set the direction for the future design or acquisition of advanced automation for damage control.

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