Abstract - Since 1991, the Research and Development (R&D) group at Lockheed Martin Canada (LM Canada) has been developing and demonstrating technologies which will provide Observe-Orient-Decide-Act (OODA) decision making capabilities/tools in Naval and airborne Command and Control (C2) for application on Canadian Patrol Frigates (CPF) and Canada’s CP-140 (Aurora) fixed wing aircraft. Over the last three years LM Canada has also established a generic expert system infrastructure and has demonstrated that it is suitable for integrating these decision making technologies into real-time Command and Control System (CCS). However, before these technologies become integrated into the C2 of any operational platform it is important to understand how should these decision making tools function and be integrated into the CCS to ensure that the human operators trust, accept and use these tools successfully. To help understand such issues LM Canada performed a literature survey and collected and analyzed over 600 papers on this subject. This paper presents the results of this survey and some conclusions made for Naval C2.

Keywords: Decision Support Systems, Blackboard, Testbed

1. Introduction

Canada’s Halifax Class Canadian Patrol Frigates (CPF) and CP-140 (Aurora) fixed wing aircraft are planned to be upgraded within the next decade to be able to deal with far more demanding threat and mission environments of today and the future, than when these platforms were designed. The computer hardware and software capabilities of today permit the development of considerably more advanced decision support capabilities, compared with the capabilities existing on these platforms currently, helping them to deal with these new environments. Over the last 9 years the Research and Development (R&D) group at Lockheed Martin Canada (LM Canada) in close collaboration with Canada’s research laboratories has been developing and demonstrating technologies which will provide Observe-Orient-Decide-Act (OODA) decision making capabilities/tools in Naval and airborne Command and Control (C2) for application on CPF and Aurora.

The research has been proceeding in a number of parallel activities including:

1. Algorithmic solutions for the decision support tools,
2. Testbed infrastructure for demonstrating these solutions,
3. Top-down systems analysis to understand the operational and mission requirements of these systems and the shortcomings of the existing systems.

The results of these research activities are incrementally being built into demonstration systems for the operators to observe and experiment with, and their feedback is being used in the next iteration.

To ensure that these research activities are conducted in a systematic manner, a number of literature surveys have been conducted over the life of this program since 1991. The first was a survey into the technologies and algorithms for decision making tools, which started in 1991 as a contract from the Defence Research Establishment Valcartier (DREV) in 1991 and is still on-going. The second is the survey initiated in 1998 of the basic and applied literature on dynamic decision making and computer-based decision support in dynamic decision-making environments, to help understand how should the decision making tools function and be integrated into the CCS to ensure that the human operators trust, accept and use these tools successfully. This survey also was conducted as a contract from DREV.

This paper presents LM Canada’s approach in applying the results of this recent survey for the
development of the Decision Support System of the CPF.

2. The Current Infrastructure

Over the last three years LM Canada has established a generic expert system infrastructure and has demonstrated that it is suitable for integrating these decision making technologies into real-time Command and Control System (CCS). Figure 1 shows the CPF testbed established based on this architecture.

The initial decision support capabilities that were implemented and demonstrated within this testbed were very close to the ones already existing within the currentCPF Command and Control System (CCS). This was done to establish the initial baseline, ensuring that the users have a frame of reference. Next, based on an internal fast review of the literature some additional decision support capabilities were added. Overall the currently available DSS capabilities include:

1. Multi-Source Data Fusion (MSDF):
   - Position estimation enhanced through:
     - Ellipsoidal gating including attribute data
     - Jonker, Volgenant and Castanon (JVC) for track/contact association
     - Adaptive Kalman Filter or IMM filters or 3 adaptive parallel filters for track estimation
   - Dissimilar data fusion (1D to 2D to 3D)
   - Target identification enhanced through automatic ID recommendations at all ranges based on any data available using:
     - Truncated Dempster Shafer for identity estimation capable to fuse any type of information
     » Fuzzyfied kinematics
     » ESM and IFF data
     » Other misc sources of information

2. Situation and Threat Assessment (STA):
   - CPF-like Threat Ranking
   - Clustering
   - Rule based allegiance
   - Commercial corridor correlation
   - Maneuvering target detection
   - Track splitting detection
   - Fast incoming target criterion
   - Ownship Missile recognition
   - Mean Line of Advance

3. Resource Management (RM):
   - CPF-like Reactive Planning:
     - Point of Intercept
     - Point of first fire
     - Target Weapon Pairing
     - Weapon Designation
     - Resource Allocation
   - Deliberative Planning:
     - Decision tree (plan) creation
     - Plan evaluation/ optimization
     - Plan repair
At this point, before any further technological capabilities are developed, it is necessary to understand how these new tools should be validated and integrated with the CPF C2, and what approach should be adopted to develop the computer based DSS (CBDSS) of the future CPF. Hence a more systematic literature survey was initiated.

3. The Literature Survey

The survey included the basic and applied literature on dynamic decision making and computer-based decision support in dynamic decision-making environments. The review was divided in four (4) distinct tasks[4]. The tasks were:

Task I -- Identification of Tools and Information Sources

Task II -- Development of a Survey Methodology

Task III -- Literature Search and Classification

Task IV -- Results Analysis and Recommendations

Close to 600 references were found using the various channels identified during Task I.

The search was done using the keywords listed in Table 1. The first column of this table presents five themes that we felt would encompass all the topics of the literature search. The second column proposes topics that subdivide a theme into more specific subjects.

<table>
<thead>
<tr>
<th>Themes</th>
<th>Sub-Themes (Phase I)</th>
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<tr>
<td>Computer-based decision support</td>
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<td>Decision Support Systems (DSS)</td>
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<td>Performance Support Systems (PSS)</td>
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<td>Trust in knowledge-based systems</td>
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<td>Process control and computer-based aiding</td>
<td>Generic tasks, Work procedures</td>
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<td>Ecological interface design</td>
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<td>Human Performance, Mental workload</td>
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<td>Cognitive styles, Human expertise</td>
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The literature found at this point was analyzed and further sorted based on their pertinence on the CPF CCS.

Based on the findings in the first three tasks it was concluded that the Results Analysis and Recommendations can take a number of different perspectives:

1. A theoretical analyses of the realization of a computer-based DSS for the future shipboard CCS that should be part of the integrated combat system. This includes summation from the Literature Survey of the concepts, models, methods, results, principles and guidelines for building dynamic systems that can help real-world decision-makers do their job more effectively and safely. This study addressed the new discipline of Cognitive Engineering (CE), the characteristics of dynamic and naturalistic environments and of the tactical combat environment, different levels of automation in computer-based systems and the place of a DSS, how to model a work domain or a complex system, the concept and characteristics of naturalistic decision making, different models of human behaviour and decision making, characteristics of naturalistic decision making, the question of how to aid the human operator at work, Ecological Interface Design (EID) framework and a proposal for improving it and presented several recommendations for building a well-engineered DSS within CCS.

2. A more practical, but generic approach for establishing a CBDSS within an existing large CCS. This approach recommended a complete spiral process for Human-Machine System Design that takes into account both human and technological aspects of system development in the specific context of the design and implementation of a CBDSS for the Halifax class ships. For each phase of the development process a set of potential human engineering tools have been described, in some cases a preferred
approach was selected, in others the question was left open until the issues are better understood. The following tasks have been identified as the cornerstones of the CBDSS development process in each phase of the spiral:

- System Analysis,
- Task Allocation,
- System Development and implementation,
- HCI, developed using a prototyping approach,
- System Evaluation, with 3 distinct areas of interest: (1) Function Usability; (2) Operational Impact; and (3) User Fit.

3. The third perspective was to address the specific example of the technologies currently under development at LM Canada for the Halifax class ships and their impact on the functions on the frigate operators.

The next section focuses on the generic approach for establishing a CBDSS within an existing large CCS.

4. **The CBDSS Development Approach**

This approach is based on the theoretical analyses of the realization of a computer-based DSS for the future shipboard CCS that should be part of the integrated combat system, and the identified and recommended approaches for Cognitive Analysis in the surveyed literature. It tries to present these methods in a structured frame, from the perspective of System Design, taking into account various constraints that are often left aside in cognitive engineering literature (e.g., technological uncertainty, compatibility with accepted System Design Frameworks, feedback loop after system evaluation, etc.). It also introduces constraints and requirements driven by the scope and specific context of a decision support system for the Halifax Class ships.

The purpose of this section is therefore to present a global approach to Human-Machine Systems Design that takes into account both human and technological aspects, and that is suitable for the development of a CBDSS for the Halifax Class ships.

The current CCS of the Halifax Class was developed under a so-called “classical” System Design framework. Given the computer power available back then, which directly impacted the level of automation and the amount of information available to the operator, the CCS design emphasized primarily the automatic system; the so-called Threat Evaluation and Weapon Assignment (TEWA) system was (and still is) performing mostly numerical and simple rule-based calculations, while most of the higher-level (cognitive) activities were left to a team of operators.

This approach to System Design aims to incorporate both the technology and the operator under a so-called Cognitive System Design Framework. In particular, we want to identify which of the approaches described in the literature is better suited for the development of a CBDSS in the specific context of the mid-life upgrade of the Halifax Class.

From the cognitive engineering and system design literature, a common trend in the way human factors should be included as part of the traditional system design approach can be identified. Figure 2 is drawn from a combination of a number of approaches to system design such as human-machine system design “frameworks” and user-centred system design methods (built from [5] and [6]).

![Figure 2: High-Level Components of a Human-Machine System Design Framework](image)

This representation of the system design process seems quite “natural” to any experienced system or software designer, except that it allocates a larger place for concerns about the end user in the early stages of the design. The main difference is the dual nature of the subsystems development phase, for which the authors recommend a two-team approach, since typically the “human factors” experts generally will not be “technology” experts, and vice-versa. It is assumed that the “human factors” team will be heavily involved in the interface design and system testing phases.
This picture, even though it seems complete and coherent, lacks a major component, namely the sequence and feedback loops, both between AND inside each subphase.

Literature on system design presents at least three mature life-cycle methodologies that have been extensively used and documented in the past to develop large software systems: Waterfall, Prototyping and Spiral.

Before we select one of these System Design approaches, and make it compatible with cognitive engineering guidelines and methodologies, we need to identify the various constraints and considerations that will drive our choice. The following constraints and points have been identified from the literature, as well as from our knowledge of the context of Halifax Class and DSS issues:

1. It is widely accepted that for the design of complex systems such as the current DSS, a Top-Down approach is recommended. This means that the system development should proceed from the general to the specific in terms of its components; for example, system analysis should first describe the global picture, then refine this picture in terms of subsystem, components, tasks, etc. until the system is defined well enough to allow design and implementation. This view is compatible with all the models presented above.

2. Task splitting, i.e., the allocation of functions between the operator and the automatic system, requires a good estimate of the “algorithmic” performance of the automatic part of the system. Unfortunately, in some systems these algorithms won’t be developed and tested until after the task splitting activity. Many cognitive analysis papers fail to take technological developments into account, thereby implicitly assuming that little technological uncertainty remains at the design phase and that the project risk mostly lies in the task splitting and interface design activities. These assumptions are incorrect in the case of a CBDSS for the Halifax Class. The design framework that will be selected will comprise a System Evaluation phase which should validate some high-level concepts such as User Fit (Situation Awareness, Communication Effectiveness) and Operational Impact of the complete integrated system. Because of the scope and complexity of the project, because of unpredictable technological performance, and also because of some unavoidable “ad hoc” task allocation included in the initial design, it is very likely that at the system evaluation stage, some initial task allocation decisions are overturned, thereby impacting the whole design and implementation cycle. Therefore the selected approach should provide a feedback mechanism to properly address incorrect task allocation or performance prediction, from the results of the evaluation of the joint human-machine system. This strongly suggests a spiral approach to system design.

3. An important paradox exists throughout the cognitive engineering literature, when approaching the problem of selecting a “cognitively sound” system design framework. This paradox is well described in [6]:

“(literature on human-system interactions) clearly establishes a pressing need to evaluate throughout the system development cycle, from concept formation to final acceptance and testing. (…) There is a balance to be achieved between conflicting needs. On one hand there is the need to accurately predict final system performance in the field with typical users working under realistic conditions. On the other hand, this prediction needs to be based on something less than the system itself. In particular, major decisions made at the concept level that misunderstand the nature of user needs or the operational environment, need to be caught before there has been a major investment in design or production.”

This implies a “testbed”, and the closer it is from the expected “final” system, the better the input to the system design. We are therefore caught in a situation of “deadlock”, where we would need a working prototype of the system in order to properly design this system in the first place. In the absence of a prototype of the “final” system, the designer must rely on two inputs: an existing, incomplete system on which experiments and observations can be made according to cognitive engineering principles, and a set of “educated guesses” on the optimal “final” system. Clearly, the larger the gap between existing and final system, the larger the number of designer’s “guesses”, the bigger the risk of identifying major misallocations and design problems at the later stages, and the larger the cost of iterating on the design and implementation to correct them. The
selected framework should therefore try to minimize - or to segment - the gap between the “initial” and “final” system. Again, this strongly points towards a spiral approach to system development.

4. A serious concern with large-scale projects such as a DSS for the Halifax Class is the risk that several system requirements change in the course of the project, or that new ones appear as a result of changing doctrine, main mission objectives, input sources or information needs. The scope and nature of the project also makes it very unlikely that all system requirements will be correctly identified and addressed up front at the beginning of the project (i.e., in the first few years). These considerations call for a framework which allows incorporation of new requirements late in the system development cycle, something the waterfall approach does not permit in principle.

5. Another issue that follows directly from the previous consideration is the intended scope of the whole CBDSS design process. This will drive the important question as to where to start the investigation, what constitutes an acceptable risk and what level of effort is realistic in the context of the project. Sure enough, an ideal analysis would incorporate a complete redefinition and redesign of the control process on Halifax Class, relying on a complete, scientifically accurate, in-depth analysis of the work and task domains, and detailed models of the cognitive processes of the team of operators. Given the current context of the timelines, budgets and expectations, the affordability of selecting such Cognitive Analysis Frameworks (CAFs) is not obvious.

1. Along the same line, a point that should not be overlooked is that the Halifax Class ships are already operational, and fully functional given today’s operational requirements and information sources. The known shortcomings/deficiencies of the existing Combat System are not likely to be judged significant enough to justify any major redesign of the decision support systems available to Halifax Class operators. Therefore it is probably unnecessary to aim for a complete redesign of the whole system, and it is likely that any new CBDSS for the Halifax Class will have to build up to a certain extent on the existing architecture and algorithms. As a consequence, the selected approach will probably need to accept constraints dictated by the existing Halifax Class system as a key input of the analysis.

All these concerns and issues directly impact the choice of a suitable high-level system design framework useable for the development of a CBDSS for the Halifax Class, and also affect (even though to a lesser extent) the recommendations we can make on specific Human-Machine system methodologies to be used in each phase of the System Design life cycle.

Considering the issues mentioned above, and considering the respective advantages and drawbacks of each proposed framework, the recommended approach to Human-Machine System Design is to follow a Spiral approach, as detailed below.

If the Waterfall approach was seen as a potential approach at the start, despite the scope of the project, the need to support potential design iterations, the
number and complexity of initial system requirements, as well as the potential consequences of late discovery of requirement or task allocation problems are all serious concerns, which make the waterfall approach extremely risky and impractical for the design and implementation of a CBDSS for the Halifax Class.

The Prototyping approach is not suitable as a framework for the complete system development, first because of its less formal structure, and also because it suffers from some of the drawbacks of the Waterfall approach, namely the fact that the requirement analysis and task allocation are made up front, at the beginning of the project. However, the prototyping model is very appropriate for some of the components where a large amount of technological uncertainty remain and which involve a research component, for instance in the area of software and algorithms development. The Testbed and HCI development constitute other examples. Such a prototyping development of subcomponents is intrinsic to the spiral approach proposed for the complete system.

The Spiral model of System Design shown in Figure 3 allows an iterative sequence of requirements/ design/ development/ evaluation cycles, incorporating a prototyping approach to system development as a risk mitigation mechanism at each new cycle of the spiral. This framework allows the customer to reduce the risk by periodically reviewing the requirements and evaluating a “completed”, although not exhaustive, working system. It also allows to naturally take into account technological uncertainty by using intermediate steps to reduce the gap between the current and the final CCS, each phase feeding the next with a better understanding of system requirements.

This high-level spiral development model describes the general activities to be performed and their sequence and feedback loops.

Each cycle of the spiral development starts with a requirement analysis, drawing from analyses of the work domain, system tasks and operator models, using analysis tools described further down. A risk analysis is then performed, followed by a “go/ no go” decision. It is assumed at this stage that only a subset of the complete CBDSS requirements will be considered at the initial cycle, with iterative additions made in subsequent phases. The same goes for the input analyses which will also increase in depth and breadth at successive iterations of the spiral process.

Based on the selected requirement system architecture will be defined, together with a rigorous function/task allocation activity. The results of this phase will feed a dual development phase: a first, so-called “cognitive” development team will investigate the structure and activities to be performed by the team of operators, while a second “technological” team will develop a prototype of the expected functionalities. Because of the expected level of uncertainty, this technological development will follow a prototyping approach, including implementation and unit testing of the components involved. This phase culminates in a quick validation of the initial task splitting and system design; in the case of a serious technological problem or task misallocation resulting in obvious performance degradation, it might be necessary to go back to the system design phase for a revision of task allocation (dotted line) before going to final system evaluation.

Finally, a HCI is developed from the previously identified tasks to be performed by the operator(s), following a prototyping approach. Testbed implementation follows, in order for a human factors team to evaluate the performance of the human/machine system. This evaluation results in a set of conclusions, which become system requirements for the next loop of the spiral development.

5. The Framework Application

The current CPF DSS Demonstration testbed architecture is excellently suited for application of the Refined Spiral Design framework for the CBDSS for Halifax Class, described above. Its modularity, independence of its components and flexibility in re-working/adding components will permit addressing the issues identified above. It will easily accommodate parallel “technological” and “cognitive” team investigations and any iterations they may require as a result of their analyses.

Based on the literature survey the tasks which should be included in the Halifax Class CBDSS development process include:

1. System Analysis, including:
   a) A Cognitive Task Analysis
   b) Skills-Rules-Knowledge (SRK) as a model of the decision-making process
   c) Work Domain functional analysis using the abstraction hierarchy
   d) A model of the generic task of the operator
2. **Functions and Tasks Allocation**, for which a few usable methodologies exist, but with no specific framework or methodology being particularly efficient or outstanding.

3. **System Development and implementation**, using a 2-teamed Prototyping approach.

4. **HCI**, developed using a prototyping approach and based on **EID**.

5. **System Evaluation**, with 3 distinct areas of interest:
   a) **Function Usability** (e.g., ease of use), which is well understood and for which several methodologies exist.
   b) **Operational Impact**, using pre-defined, numerical measures of performance.
   c) **User Fit** (including Situation Awareness and mental workload), which is much less parametric and precise.

The testbed can be used to incrementally experiment with and evaluate various approaches, with the aim to understand which of these methodologies can actually be implemented, whether they can be fully exploited, and to which level of detail they should be developed.

6. **Conclusion**

   Based on a Literature survey on CBDSS for Command and Control this paper selected and described a complete Spiral approach to Human-Machine System Design that takes into account both human and technological aspects of system development, which we have presented and justified in the specific context of the design and implementation of a CBDSS for the HALIFAX Class ships.

   A testbed architecture that can accommodate and facilitate such an approach was also described.

   The discipline of CBDSS for future C2 in terms of both technological and cognitive aspects is quite young, and significant more effort should be applied in analyses and evaluations in testbed environments to ensure that the user trusts, accepts and uses DSS capabilities.

7. **Acknowledgements**

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8. **References**


