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TITLE

SCIMERS: A SONAR CONTACT INTEGRATED MANOEUVRE EVALUATION AND RECOMMENDATION SYSTEM

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SCIMERS: A SONAR CONTACT INTEGRATED MANOEUVRE EVALUATION AND RECOMMENDATION SYSTEM

Todd Michael Mansell
(Australian Exchange Scientist)
Bruce McArthur
Defence Research Establishment Atlantic, PO Box 1012, Dartmouth, NS, B2Y 3Z7, Canada.

Abstract - **This paper describes the design and initial development of a manoeuvre decision aid for a towed array sonar system. The Sonar Contact Integrated Manoeuvre Evaluation and Recommendation System (SCIMERS) is being designed as an interactive decision aid, providing the tools to manipulate a representation of the undersea environment and formulate manoeuvre recommendations. SCIMERS will interface with non-acoustic data sources to acquire contact information, sensor performance prediction data, and bathymetric data. This information is evaluated to generate a geographically referenced description of where the ship should (and should not) manoeuvre. In this paper we identify the necessary functionality required to perform manoeuvre assessment and recommendation. We also describe the software architecture and present the preliminary operator-machine interface used to visualise relevant databases and the value of various manoeuvre strategies.**

I. INTRODUCTION

Compiling a picture of the undersea environment is critical to the operation of a naval ship and requires access to a wide range of information. The person responsible for generating the undersea picture typically must work closely with information from the ship's sonar sensors and must integrate this with bathymetric and sonar performance prediction information, as well as non-acoustic sensor data. This information is typically uncertain and incomplete, requiring assumptions to be made in order to compile the geographically based situational picture (geosit) and to subsequently perform situation assessment. It is also necessary for the ship to employ its sensors optimally to resolve uncertainties.

SCIMERS is designed to assist in this process by formulating the locally optimal (best), next manoeuvre by providing situation assessment, tactical reasoning, and data visualisation tools. SCIMERS is designed to perform five fundamental functions: (1) gather information from a variety of sources (which may include sonar contacts, radar contacts, as well as bathymetry, weather and performance prediction maps) and assemble them in a working database; (2) resolve and fuse uncertain, incomplete and conflicting contact information for geosit compilation; (3) reason using contact and environmental information to perform situation assessment and "what if" testing; (4) generate a manoeuvre recommendation that satisfies goals ranked by the user; (5) concisely display a manoeuvre recommendation and all necessary, supporting information.

SCIMERS is being designed to access all relevant data and information in a non-intrusive manner. This requires interfacing with the ship's existing performance prediction systems, sonars and the command plot (a display of the combined air, surface and undersea geosits). The situation assessment will be achieved using artificial intelligence techniques; manoeuvre recommendations will be produced using artificial intelligence planning techniques.

A significant aspect of the SCIMERS system is the development of the operator-machine interface (OMI). Central to this interface is a plot of the geosit that allows contact information and manoeuvre recommendations to be overlayed on bathymetric or performance prediction information.

SCIMERS is being developed as an at-sea decision aid, hence all functions must be performed in near real-time. The current aim is to be able to provide a manoeuvre recommendation within three minutes. SCIMERS is currently in early development with the software architecture design complete and implementation of the various components scheduled to begin shortly.

II. SOFTWARE ARCHITECTURE

The software architecture for SCIMERS is divided into a number of applications-based modules, as illustrated in Figure 1. This section provides an overview of the functions performed by SCIMERS, and outlines some of the significant issues associated with developing a decision aid that must interface with numerous subsystems and conduct intelligent reasoning tasks. We will refer to these subsystems as software modules for the remainder of the paper.

A The Data Collection Module

The data collection module is primarily concerned with gathering information from all the available sources and assembling them in a working database. SCIMERS uses its own databases to allow the user to do "what if" and multiple-hypothesis testing of propositions without affecting the ship's command plot.

SCIMERS will assemble the following information into working databases:

- surface and subsurface sonar contacts.
- Target Motion Analysis (TMA) information.
- surface radar contacts.

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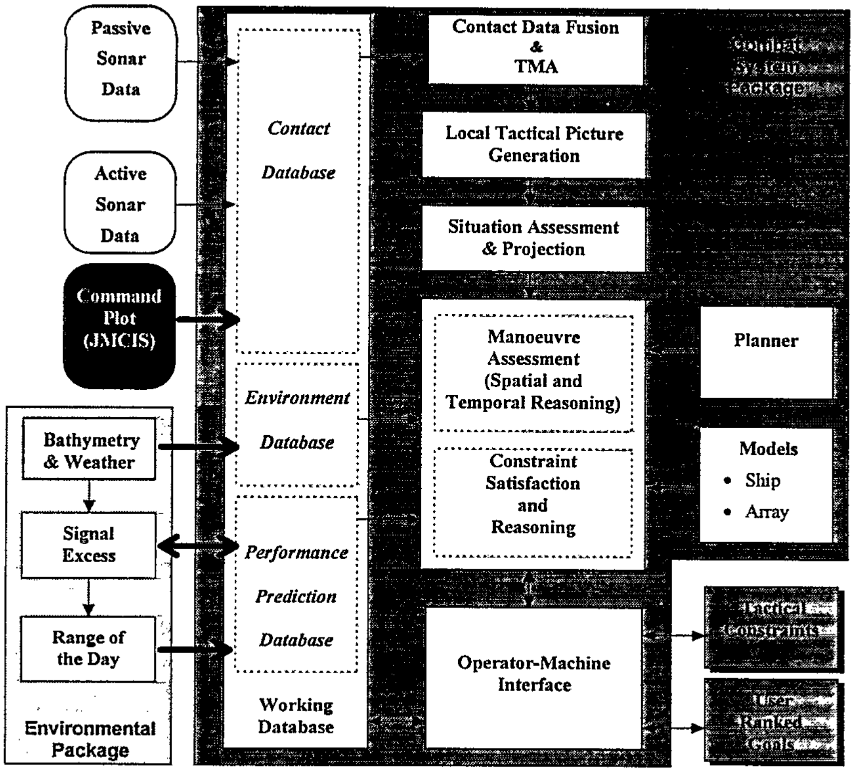


Figure 1: Software Architecture for SCIMERS.

- signal excess maps.
- bathymetry maps.
- weather information.
- bathythermograph based acoustic range predictions.

The above information will be provided via networked processes that run outside SCIMERS but which communicate through a common operating environment. Section J provides a discussion on how and where this information is obtained.

B Geosit Manipulation

The generation of the geosit requires the fusion of a platform's sensors (e.g., sonar, radar, etc.) with off-platform sensor and intelligence information. The geosit typically displays best estimates of contact position, and classification. A SCIMERS user would utilise this plot to evaluate the current situation and, along with environmental and strategic information, to formulate a course of action (e.g., change current course, speed and/or sensor depth). Geosit generation is a crucial precursor to the manoeuvre generation process.

SCIMERS provides the user with a tool for manipulating the geosit to allow the user to associate tracks and fuse information. Ideally, the command plot will provide an accurate and precise representation of the geosit. However, this is often not the case as uncertain and incomplete information are usually all that is available to generate the air, surface and undersea geosits. The resulting command plot is often a conservative estimate of what is known about the environment. The geosit module in SCIMERS provides the user with the tools to make "what if" assumptions about the contact classification and data associations before conclusive information has been obtained. The associations (created or destroyed) and the classification designated in this module are *not* promulgated back to the underwater or command plots.

SCIMERS uses some of the underwater geosit generation tools to integrate command plot data and postulate possible target locations and classifications. This software module is composed of algorithms for signal tracking, data fusion and target motion analysis (TMA), as well as a set of associated databases [1]. The databases hold all tracked acoustic signals which are associated with a given contact. Bearing and frequency information obtained from the databases are utilised in the situation assessment module (Section C) for inferring target behaviour. Other databases hold all possible localisation solutions for each contact produced by executing one or more TMA algorithms. Importing contact and target information into SCIMERS gives the operator flexibility to utilise different localisation solutions (ie, choose alternate TMA solutions) and develop "what if" scenarios.

The SCIMERS geosit module is currently undergoing test and evaluation. At present, the software generates a picture of the surface and subsurface environments using passive sonar information [1]. This software is being enhanced to include active sonar information, to produce the sonar geosit. The sonar geosit will then be integrated with organic, non-acoustic information to produce a common geosit using a feature level fusion architecture [2] based on evidential reasoning [3].

C Situation Assessment and Projection

The situation assessment and projection module is responsible for performing situation assessment and predicting how the geosit will change during an own-ship manoeuvre. Situation assessment is performed by extracting salient features from the geosit, bathymetry, performance prediction maps and own-ship information to deduce significant features about the current situation.

Projection provides an extrapolation of the geosit over the forecast planning horizon. This is achieved by anticipating the targets' tracks and manoeuvres based on their observed track history, and their assessed objective.

SCIMERS will perform situation assessment using contact information (such as location, movement vector and classification) from the geosit. Contact classification may range from general terms such as surface, subsurface, biological or unknown, to identifying individual units. In addition, the situation assessment module attempts to clarify the geosit, using bathymetry and additional sonar data, to determine the intent of each contact. For example, bathymetric information may be used to predict how a target may manoeuvre over time or estimate a contact's location based on its assessed intent. Other information such as a change in bearing rate, range rate, doppler or perhaps even SNR may indicate the target's strategies (e.g., hide, search, retreat, etc.).

Initially, the operator will assess the target's strategy and manually enter this information using a dialog box. However, we are currently evaluating evidential reasoning techniques as a mechanism for semi-automating this process using a toolkit called Horizon [4].

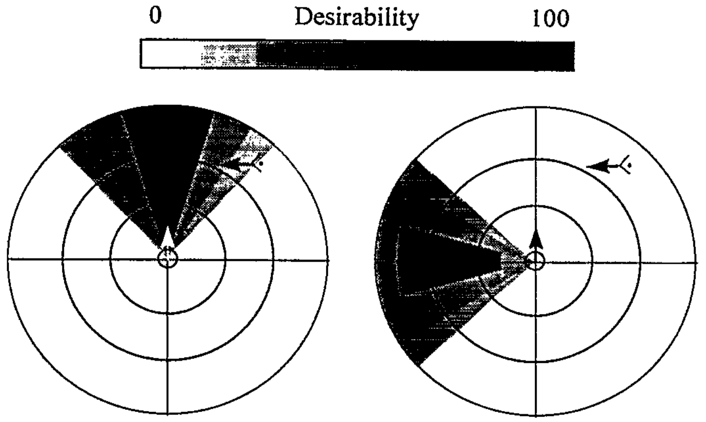
D Goals

When conducting operations that require tracking contacts (e.g., drug interdiction), the command team will seek to formulate a manoeuvre that optimises a combination of mission critical objectives. These objectives have been characterised within SCIMERS as high level (abstract) goals and low level (detailed) sub-goals. The term goal is used to describe the aim of the next manoeuvre (such as *localise contact forthwith*, *localise contact from a safe distance*, *covertly localise contact*, etc). At the lower level, we use the term sub-goal to capture a detailed description of one particular objective of the operation. Some typical sub-goals include *maintain signal*, *reduce range uncertainty*, *improve SNR*, *maintain true bearing*, *maintain relative position* or *avoid counter detection.*

Goals in SCIMERS are programmed at knowledge engineering time and characterise what our domain experts believe are the salient features of contact tracking manoeuvre objectives. Each goal is described by a number of sub-goals quantitatively ranked to optimise a particular manoeuvre strategy. For example, the goal *covertly localise contact* is achieved by satisfying sub-goals *reduce range uncertainty* and *avoid counter detection.* Currently, the default mode of operation is to have the user select between a number of standard goals.

The alternative to using a goal list is to allow the operator to rank the sub-goals. This process involves having the operator quantitatively rate the utility of each sub-goal according to his/her measure of that sub-goal's significance to the particular manoeuvre strategy. In essence, the user is customising each sub-goal's contribution to the overall objectives of the next manoeuvre. However, for reasons discussed at the end of this section, this is not the preferred mode of operation.

An algorithm is provided to generate the constraints associated with each sub-goal. These algorithms could be a function of the operational limits of the system, contact geometry, and/or additional information (such as the range-of-the-day calculation). For example, the sub-goal *maintain relative position* will generate a constraint cost/benefit surface that is highest when the own-ship's course and speed match that off the target (illustrated in Figure 2). However, more complicated sub-goals, such as *improve SNR,* require computing complex functions that often include sonar performance prediction calculations.



Maintain True Bearing

Maintain Relative Position

Figure 2: Constraint maps generated by two sub-goals.

The constraints plot generated by a sub-goal can be viewed as a cost/benefit surface where each point in the plot coincides with a point on the geosit. Each sub-goal's constraints are represented as a 2 dimensional shape (eg polygon, ellipse, circle) on this plot. The cost/benefit associated with each point in the plot is a measure of desirability associated with the ship being placed at that location.

A number of methods for combining the overlapping constraint areas are discussed in the literature [5]. These generally focus on the non-trivial task of determining where multiple areas overlap and how to calculate the combined utility value for each point in the plot.

While it might be a straightforward process to find the best solution for an individual sub-goal, it is often impossible to find one solution that is optimal for all sub-goals simultaneously. For example, a manoeuvre that satisfies the sub-goals *maintain true bearing* and *maintain relative position* (Figure 2) will only be optimal for each sub-goal if the contact has the same course and speed as the own-ship. Under all other conditions these sub-goals will be in conflict to some extent.

To combine two or more constraint plots SCIMERS uses a weighted averaging rule. We define the benefit, $B_{i,j}$, at some point in the combined cost/benefit plot for the goal, x, to be:

$$B_{i,j}(x) = \sum_{\forall y \subset G} k(y).B_{i,j}(y)\,, \qquad (1)$$

where y is a sub-goal belonging to the set of all sub-goals, G, and k(y) is the weighting constant for sub-goal y. This algorithm can be used to combine the constraint maps of individual sub-goals to produce a combined sub-goal constraint map, or CM_{Σ}.

This formula for combining constraints requires the user to provide a consistent weighting factor for each sub-goal. If the weighting is disproportionately high for a particular sub-goal, then the solution cost/benefit function for the top-level goal will be adversely biased. For consistency and accuracy reasons we prefer to have the operator select a goal rather than having him/her weight various sub-goals.

E Performance Prediction Models

Performance prediction models provide valuable predictions about how the sonars will perform in the prevailing acoustic environment. The type of performance prediction information used by SCIMERS are the signal-excess plot[1] and probability of detection maps.

SCIMERS will use existing sonar performance prediction software to generate signal excess or probability of detection maps as a basis for calculating the best, next manoeuvre. These maps are used to generate the constraint map for goals such as *improve SNR*, *maintain signal* and *avoid counter-detection.* These maps will be stored in a database and can be displayed as an underlay in the operator-machine interface. This is discussed further in Section I.

Active sonar is often perceived as being a sensor capable of detecting all contacts in a volume of water in a manner similar to radar. However, this sensor is sensitive to environmental conditions and may, under many conditions, have a low probability of detection (POD). The limitations of active sonars can be presented by POD maps or signal excess maps. The environmental data typically input into these models are a combination of sound velocity profile, bottom type, sea state, ambient noise level, range-dependent depth, and sonar operating parameters. The output of these models provides reasonable estimates of expected detection ranges. In addition, these maps also highlight regions where echoes would fall significantly below the sonar's detection threshold.

Similarly, passive sonar performance prediction models use information such as bathymetry (bottom type and slope), temperature profile, salinity, source levels and sonar operating parameters, to predict signal excess or POD.

An alternative to predicting some of the sonar parameters is to measure these in situ. This approach requires some assumptions about the environment at the beginning of an operation, but normally provides more accurate characterisation of the environment. Integration of this technology into the sonar performance prediction system would be invisible to our MDA as SCIMERS only utilises the output from this software.

F Representation and Reasoning

A significant portion of SCIMERS research and development has been devoted to establishing a method for representing and reasoning with current information. In this paper we use the term *representation* to imply the means by which objects and their relationships may be symbolised, and the term *reasoning* to mean the process of drawing inferences and conclusions based on available information described by our representation scheme. This module provides SCIMERS with the functionality to characterise the environment and reason how best to achieve goals.

The representation scheme used by SCIMERS will be sufficiently expressive to enable it to capture:

- spatial features (e.g., bathymetric features and sonar shadow zones).
- spatial relationships between objects (e.g., significant geometries).
- temporal features based on a contact's history (e.g., last course alteration).
- temporal relationships between contact movement and goals (e.g., zigging ship).
- contact information (e.g., classification).
- behaviour identifiers (e.g., flee, hide, etc.).
- causal relationships (such as the effect certain actions have on the geosit).

SCIMERS uses an own-ship centred polar coordinate geometry to represent contacts and spatial features. In addition, spatial relationships are described by regions or geometric relationships, and temporal relationships are described by time varying functions. Finally, contact information and identification use a linguistic description to classify the contact or describe its behaviour. Most of these descriptions may contain measures of uncertainty, (e.g., area of uncertainty).

The reasoning functionality adopted by SCIMERS provides the capability to analyse the movement of contacts in time and space, as well as characterise relationships and interactions. SCIMERS will use a combination of spatial, temporal and plausible reasoning systems in order to make inferences about a planned manoeuvre. Spatial reasoning allows the analysis of positions, features, and motion in space; temporal reasoning provides the ability to represent and reason about time states. Finally, plausible reasoning provides a mechanism for reasoning about information that is uncertain and incomplete, similar to the human ability to form an educated guess.

Ultimately, SCIMERS' reasoning module is responsible for creating constraints that are not determined by the sub-goals. This includes significant geographic features and time constraints due to varying contact geometries, own-ship kinematics, and sensor kinematics. These spatial and temporal constraints are fused to form the derived constraint map, CM_D. The CM_D and CM_Σ are integrated using equation 1 to produce the global constraint map, CM_G.

For example, the reasoning module will locate surface contacts from the geosit and add an area of high cost to the constraint map associated with each contact. The size and shape of this "high cost area" is dependent on the contact's location, speed, course and classification. This is to avoid placing the own-ship in danger of collision with other surface traffic. These constraints are added to the CM_D which in turn is integrated with the CM_Σ to produce the CM_G.

This module provides SCIMERS with the capability to describe and reason about the effect of actions on the world and evaluate "what if" scenarios (i.e., determine the significance of a user-defined manoeuvre). The representation and reasoning techniques used by SCIMERS are also a

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[1] Measure of where signal strength is likely to exceed the detection threshold of the sonar.

necessary component of the manoeuvre planning module discussed next.

G Manoeuvre Planning

Planning can be described as composing a course of action that transforms the world from its current state to a desired goal state. In the SCIMERS domain we are concerned with generating the best, next manoeuvre. A manoeuvre recommendation for a towed array equipped ship usually consists of a small number of low level actions. Each action is described by a 4-tuple $<x_c, x_s, x_d, x_t>$ over the variables *course*, *speed*, *array depth*, and *time*, respectively.

SCIMERS will use a mixture of computational geometry [5] and optimal search techniques [8] to produce a locally optimal, next manoeuvre. However, SCIMERS will not take into consideration long-term strategic goals of the command team (hence it is said to be locally optimal). It is up to the operator to adapt a manoeuvre recommendation to be consistent with the mission's long term goals[2].

The computational geometry approach to best, next manoeuvre planning, as used by Benjamin *et al* [7], can be viewed as a search operation where the goal is to maximise expected benefit. A number of optimal and sub-optimal search algorithms are discussed in the literature [8]. The A* algorithm stands out as a computationally efficient, optimal algorithm that has been successfully applied to path planning problems [9] in the past.

The A* algorithm is a combination of the greedy search algorithm and the uniform cost algorithm [8]. The greedy search is a sub-optimal algorithm that minimises the estimated cost of the goal, $h(x)$, and thereby cuts the search cost considerably. The uniform-cost search is an optimal algorithm that minimises the cost of the path so far, $g(x)$, but can be very inefficient. The A* algorithm combines the best of these properties to evaluate $f(x)$, the estimated cost of the cheapest solution through x:

$$f(x)=g(x)+h(x). \qquad (2)$$

The restriction is to never choose an h function that overestimates the cost of the search goal. The h function should always be an optimistic estimation of the cost of solving the problem.

The SCIMERS planning approach can be summarised by the following 4 steps: (1) mapping goals and constraints to an own-ship centred plot; (2) combining the constraint maps to produce the combined sub-goal constraint map, CM_Σ; (3) adding the temporal and spatial reasoning constraints to produce the CM_G, and; (4) search over the final constraint map to find the best next manoeuvre.

This methodology provides the following advantages:

1. the reasoning process is simplified, as reasoning is reduced to generating constraints on a common frame of reference represented by the own-ship centred plot.
2. planning becomes a search problem.
3. explanation can be achieved by displaying each of the constraint areas on the plot and singling out those areas that contributed the greatest utility to the recommended area.
4. it is potentially fast, depending on the algorithm used for calculation.

The disadvantages of this methodology are that it is not easily amenable to doing more long-term planning, or even looking a few moves ahead. Further, the computational complexity of this approach increases rapidly for complex constraint areas (oddly shaped polygons) or a large number of these shapes.

H Hydrodynamic Models

The use of hydrodynamic models will be necessary to allow SCIMERS to realistically model own-ship manoeuvres and to determine towed array stability (linear and horizontal) during turns. These models will be used to modify the path produced by searching the CM_G to refine the best, next manoeuvre recommendation.

In particular, SCIMERS will incorporate the following models:

- A ship dynamics model to represent how the tow ship manoeuvres given the sea-state and ship handling characteristics. This model will provide realistic ship positioning throughout a manoeuvre.
- A towed array hydrodynamic model to determine how long the array will take to recover from an own-ship manoeuvre. This model will be used to provide time and location where the towed array data is likely to be classed as unusable. These models can also predict depth excursions during a manoeuvre and therefore be used to alert to array grounding.

These models can be fairly crude and may be upgraded if or when it is deemed necessary. Simple models can be based upon look-up tables of ship turn rates at different speeds and time for the towed array to stabilise based on tow cable length, total bearing change, turn rate and speed.

I Operator Machine Interface

The operator machine interface (OMI) is considered an integral part of SCIMERS. Without a well designed OMI the decision aid may never be accepted by the operators, no matter how powerful the tools it provides. A good OMI must be intuitive to use, adaptable to different situations, and provide access to all necessary information. Further, this information must be displayed in a format that can be easily interpreted and evaluated by the operator. A mock-up of the proposed SCIMERS's main interface window is shown in

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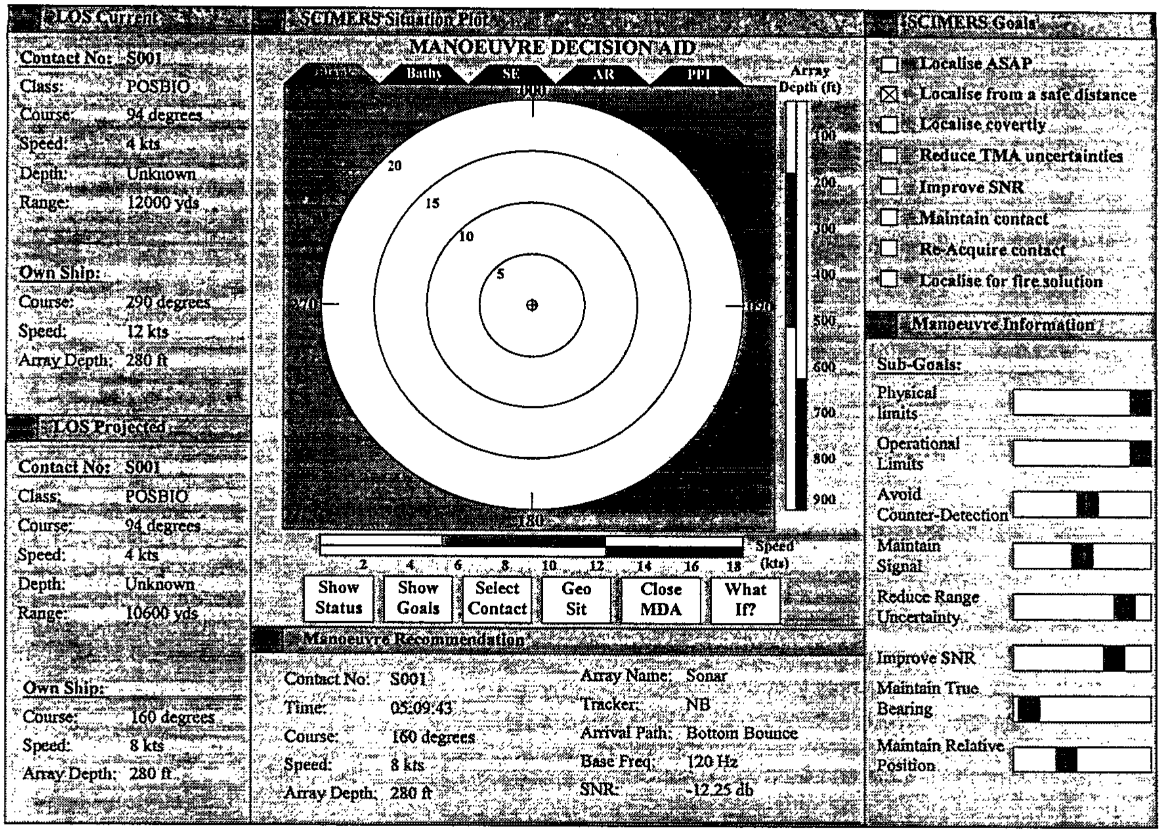
[2] Plan recognition techniques [6] may be used in the future to enable SCIMERS to recognise and incorporate long term planning strategies into the construction of locally optimal plans.



LOS Current

Contact No: S001
Class: POSBIO
Course: 94 degrees
Speed: 4 kts
Depth: Unknown
Range: 12000 yds

Own Ship:
Course: 290 degrees
Speed: 12 kts
Array Depth: 280 ft

LOS Projected

Contact No: S001
Class: POSBIO
Course: 94 degrees
Speed: 4 kts
Depth: Unknown
Range: 10600 yds

Own Ship:
Course: 160 degrees
Speed: 8 kts
Array Depth: 280 ft

Manoeuvre Recommendation

Contact No: S001
Time: 05:09:43
Course: 160 degrees
Speed: 8 kts
Array Depth: 280 ft
Array Name: Sonar
Tracker: NB
Arrival Path: Bottom Bounce
Base Freq: 120 Hz
SNR: -12.25 db

SCIMERS Goals

☐ Localise ASAP
☒ Localise from a safe distance
☐ Localise covertly
☐ Reduce TMA uncertainties
☐ Improve SNR
☐ Maintain contact
☐ Re-Acquire contact
☐ Localise for fire solution

Figure 3: The Proposed SCIMERS user interface window.

Figure 3. This OMI draws on a design proposed for MDA[3] [7].

The OMI will allow the user to interact with most of the SCIMERS modules mentioned above. The user can monitor/select the information to be input into the working database, initiate the interactive geosit generator, perform situation assessment, rank goals based on the current situation, supervise the construction of a manoeuvre recommendation, and, evaluate "what if" scenarios.

The proposed SCIMERS OMI (Figure 3) is divided into 6 areas. Central to the display is the SCIMERS situation plot. This window graphically displays necessary information on an own-ship centred geographical plot. From this window, the operator can view the sonar geosit (surface, submarine and biological contacts) or the command plot (containing air, surface and submarine contacts). This information may be overlaid on a bathymetric map, signal excess map, constraint map (including the CM_Σ, CM_D, CM_G, or individual sub-goals CMs) or a blank (uncluttered) display.

The manoeuvre recommendation is displayed in a window below the situational plot as well as on the situational plot, with recommended array depths and ship speeds appearing in a vertical and horizontal bar respectively. Other windows display current own-ship and contact information, projected own-ship and contact information, manoeuvre data (including data on anticipated effects on the sensor suite), goal selection, and sub-goal satisfaction (a measure of how well individual goals are achieved by the manoeuvre).

J System Integration

The integration of tactical decisions aids into an at-sea environment often poses significant integration problems. One issue has been identifying how the information sources (sonar tracks, sensor performance prediction, hydrodynamic models, ...) are going to interface with the decision aid. The key to SCIMERS input requirements is to build upon a common operating environment (COE). One such possibility is the Joint Maritime Command Information System (JMCIS) [10] along with a number of third party applications.

The JMCIS COE is an open architecture and a software development environment that offers a collection of core services and command decision aids. The idea is to provide a standard environment, a set of standard off-the-shelf components, and a set of programming standards that describe how to add new functionality to the environment. By developing JMCIS applications the developer can:

1. leverage from common services like charting and communications.
2. provide a common environment for in-service command information systems and defence research & development, thereby reducing the time lag associated with getting technology from the laboratory into service.

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[3] MDA's OMI design was generated by Susan Kirchenbaum of the Naval Undersea Warfare Centre, RI, USA.

The JMCIS COE establishes standards and provides baseline functionality; a JMCIS developer extends this baseline and adds functionality to meet specific requirements. This is achieved through what are termed JMCIS Segments [10] (or applications that run under JMCIS).

The infrastructure to perform sonar information processing is provided by a segment that sits on top of JMCIS. This segment is a real-time environment that facilitates the development and evaluation of surface ship and submarine combat system prototypes. Signal tracker information, target motion analysis as well as some inter(intra)-sensor fusion and command plot functions are all provided through this segment. SCIMERS will interface with this segment in order to obtain the necessary information. In addition, SCIMERS will obtain climatological and sonar performance prediction information from a currently available JMCIS-based package.

III. SUMMARY

This paper describes SCIMERS, a manoeuvre decision aid currently under development at DREA. The challenges facing the development of this decision aid are discussed and the tasks required to perform manoeuvre evaluation and recommendation are identified. The major functions performed by SCIMERS are:

1. integration of active and passive sonar information to generate the local geosit.
2. perform situation assessment and projection,
3. intelligently reason with environmental data in the context of the current situation,
4. generate a manoeuvre recommendation based on the operator selected goal, and
5. display necessary information.

Further, this must all take place within an acceptable time frame. The initial goal is to have SCIMERS produce a manoeuvre recommendation within 3 minutes.

SCIMERS is being designed as an interactive decision aid for the user with tools to assess the geosit and formulate manoeuvre recommendations.

ACKNOWLEDGEMENTS

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