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TITLE

GOAL-DIRECTED DATA INTEGRATION FOR SONAR PICTURE COMPILATION

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GOAL-DIRECTED DATA INTEGRATION FOR SONAR PICTURE COMPILATION

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ABSTRACT

This paper discusses a decision aid for managing data integration resources within a sonar picture compilation system. The system design is based on the concept, termed goal-directed data integration, that data integration will be most effective if it is used to solve specific problems detected during the process of building the sonar picture. Under the goal-directed data integration framework the process of sonar picture compilation is decomposed into a task hierarchy, with the successful completion of each task being considered to be a goal. A blackboard-based control structure is employed for prioritizing unsatisfied goals, planning sequences of data integration operations to satisfy each selected goal, and monitoring the execution of active plans. It is also demonstrated that the goal-directed representation provides a natural user interface for high-level operator control of data integration processing. Examples are presented for a passive sonar sensor and goals related to signal tracking tasks.

1. INTRODUCTION

Semi-automated systems are being developed to aid a naval command team in building a *sonar picture* representing the surface and subsurface environment. The sonar picture contains information regarding the number of detected targets, target identities, and target positions, courses, and speeds. It is compiled mainly using acoustic data, from one or more sonar sensors, and non-acoustic data, such as environmental information.

The integration of multiple acoustic and non-acoustic data sources is recognized as a key requirement for achieving accurate and efficient compilation of sonar pictures [1]. The possible applications of data integration to sonar picture compilation include: data reduction (the effective reduction of the volume of data achieved by grouping together all signals emitted by each target); tracking targets with intermittently detected and/or time-varying acoustic signatures; detection of weak signals in background clutter; separation of interfering signals from multiple targets; and, more accurate parameter estimation by integration of multiple measurements from the same signal source. To date, data integration has been performed manually by the sonar operators and the command team. However, given the volume and complexity of sonar data in multi-target multi-sensor environments, the full potential of data integration cannot be exploited without the increased use of automation.

In this paper a new framework, termed goal-directed data integration, is introduced for managing the selection of signals and data integration operations in a semi-automated sonar picture compilation system. Using goal-directed data integration, signals and data integration operations are selected as a means for resolving specific problems which arise during sonar picture compilation. It is proposed that goal-directed data integration can be more efficient than conventional data integration frameworks and, at the same time, be more easily understood by the sonar operator. The design of the goal-directed framework is based on two concepts. First, the process of sonar picture compilation is decomposed into a hierarchy of tasks, and the successful completion of each task is considered to be a goal. Second, unsatisfied goals are prioritized and sequences of data integration operations are generated which can potentially satisfy each selected goal.

The remainder of the paper is organized as follows. In section 2, the concept of goal-directed data integration is introduced through a discussion of different approaches to managing data integration. The design of the goal-directed data integration framework is discussed in Section 3. Summary remarks are presented in Section 4.

2. MANAGING DATA INTEGRATION

A key issue in data integration systems design is the process by which signals are selected for integration and which data integration operations are then applied to those signals. This is important, first because the number of signals to be integrated may be very large, particularly in multi-target multi-sensor environments, and second because there are many possible techniques for integrating the data. The complexity of the sonar data integration problem is illustrated by considering that a combination of any of the following basic data association operations may be applicable at any given point in time [1]: temporal association of intermittent signals; intrasensor[1] association between multiple signals from the same target being detected on a single sensor; and, intersensor association between signals from the same target detected on different sensors, such as multiple passive and/or active sonars. Temporal association operations also include cued searches for intermittent signals based on intrasensor associations [2].

Conventional approaches to sonar data

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[1] Intrasensor association is deemed to include association between signals from the same target being detected on a single sensor using different signal processing techniques, such as narrowband and broadband processing.

integration are represented by manual and data-driven techniques. In manual sonar data integration the human operator determines which signals are to be integrated during sonar picture compilation. Data integration is not performed on all signals but instead is used as a tool for solving specific problems relating to localization, classification, or threat assessment. In performing data integration, operators use cognitive and perceptual processing skills, previous experiences in solving data integration problems, as well as a broad range of knowledge concerning mission goals, target classes, sensors and acoustics. The human operator is also capable of communicating the reasoning behind data integration decisions to other members of the command team. The main weakness of manual data integration is the limited information processing capacity of the human operator. This weakness is demonstrated by the information overload suffered by human operators when tasked to handle large volumes of data in multisensor, multi-target environments.

In contrast, using a data-driven architecture for sonar data integration, a hierarchy of composite association hypotheses is generated by executing a fixed sequence of data integration operations on all detected signals. One commonly applied sequence is temporal association, followed by intrasensor association, and finally intersensor association. While the simplicity of the data-driven architecture is well-suited for hardware implementation, there are drawbacks to its use in those applications, such as sonar picture compilation, in which there is both a large number of signals and a high level of uncertainty in the data. This occurs because a combinatorial explosion of association hypotheses may occur when attempts are made to apply data integration operations to all hypotheses at each level in the hierarchy. In addition, the use of a fixed sequence of data integration operations assumes that the information necessary for making an association decision is available at the current level in the hierarchy or is implicitly contained in lower-level associations. Given the complex, uncertain nature of the acoustic data, efforts to control the generation of association hypotheses by deleting all but high-probability associations at each level are often unreliable.

Goal-directed data integration is a semi-automated framework for assisting the sonar operator in managing the selection of signals and data integration operations. The concept underlying the goal-directed framework — that data integration should be used as a tool for solving problems arising during the process of sonar picture compilation — is closer in philosophy to manual data integration than to data-driven integration. The design of the framework is based on the use of goal-directed reasoning techniques. A goal statement is converted into one or more subgoals that are easier to solve and whose solutions are sufficient to solve the original problem [3]. Thus the process of sonar picture compilation is explicitly represented by a hierarchy of goals, with each goal being the successful completion of a sonar picture compilation task. Data integration management is achieved by monitoring those goals which potentially may be satisfied using data integration operations. For monitored goals which are detected as being unsatisfied, sequences of data integration operations are first planned and then executed. Those parts of the goal hierarchy which are not specifically monitored provide contextual information which is used to prioritize the generation and execution of plans in cases where multiple goals must be satisfied. Attention is therefore focused on those data integration operations with the greatest potential impact on the sonar picture.

Goal-directed data integration extends a previously-developed blackboard framework for managing data association operations [4]. The framework in [4] allows for data-dependent ordering of association operations and thus provides increased flexibility over the data-driven architectures. However, there is no explicit representation for the sonar picture compilation task to which the data association operations are being applied.

3. GOAL-DIRECTED DATA INTEGRATION

Goal-Based Representation for Sonar Picture Compilation

A goal-based representation, or goal hierarchy, for sonar picture compilation is based on a model of the sonar picture compilation task. Each task which is identified as being necessary to complete the compilation of the sonar picture is considered to be a goal. Then, using a process of hierarchical decomposition, each goal can be examined at a finer level of detail by breaking it down into subgoals. The decomposition process can be continued recursively until operations are available which can directly satisfy the bottom-level goals.

One possible decomposition for the sonar picture compilation task, assuming a passive directional sonar, is presented in Figure 1. The top-level goal, "Compile Sonar Picture," is decomposed into the subgoals "Determine Number of Targets" and subsequently for each target into the subgoals, "Localize and Track Target," "Classify Target," and "Assess Target Threat Level." These represent the traditional high-level tasks involved in compiling the sonar picture. Goals relating to localization and signal tracking are expanded in greater detail. The "Localize and Track Target" goal is decomposed into subgoals related to the major factors affecting the quality of a localization solution using a passive directional sonar [5]: selection of a suitable localization algorithm; selection of appropriate models for target motion and acoustic propagation; and maintaining adequate quality on the measurement data. The "Maintain Adequate Measurement Data" goal is decomposed into subgoals for maintaining contact on the target and for accounting for sensor-related factors, such as geometric deformation or vertical arrival angle, which if neglected can result in biased or poor quality measurement data. Finally, the "Maintain Contact on Target" goal is decomposed into subgoals for maintaining contact on each of the signals associated with the target.

The relationship between goals and subgoals may be either conjunctive or disjunctive. Conjunctive subgoals (equivalent to an "AND" relation) represent a set of conditions, all of which must be satisfied to satisfy the parent[2] goal. Disjunctive subgoals (equivalent to an "OR" relation) represent a set of alternative conditions for satisfying a parent goal. An example of disjunctive subgoals is provided by the OR relation between the "Maintain Contact on Target" goal and the "Maintain Contact on Signal" subgoals. In a case where multiple signals are being tracked, it is only necessary to maintain contact on a single signal in order to maintain contact on the target. Hierarchical decomposition with conjunctive and disjunctive subgoals results in an AND/OR tree structure [6].

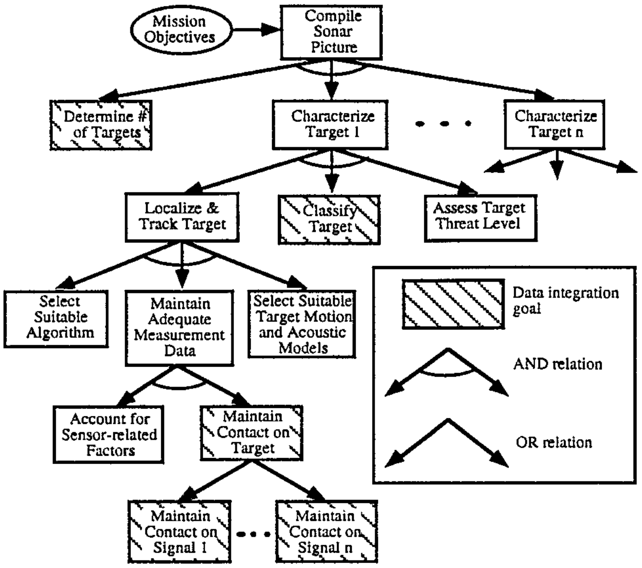

Figure 1. Goal-based representation of the sonar picture compilation task for a passive directional sonar. Goals related to localization and signal tracking have been expanded more fully. Data integration goals are defined to be goals satisfiable using data integration operations.

Certain goals in the hierarchy, termed *data integration goals*, are classified as being potentially satisfied by executing one or more data integration operations. Examples of data integration goals in Figure 1 include "Determine # of Targets", "Maintain Contact on Signal," and "Maintain Contact on Target." The "Determine # of Targets" goal may be satisfied by using intrasensor association operations to group together all signals received from each target. A "Maintain Contact on Signal" goal may be satisfied by using temporal association operations to assemble a temporal history of signal segments from an intermittent source. The "Maintain Contact on Target" goal may be satisfied by using a combination of temporal and intrasensor association operations to maintain contact on at least one signal at all times. (In each of the above examples, intersensor association operations may also be applicable in situations involving multiple sensors). Using the control structure discussed in the following section, processing resources are focused on those data integration goals which are identified as being unsatisfied.

One can distinguish between sections of the goal hierarchy whose structure is scenario-independent, and other sections whose structure may change significantly during the span of a single scenario. Generally the top-level goals in the goal hierarchy will be scenario-independent, as the high-level objectives of the tactical picture compilation task do not change. Lower-level goals, such as maintaining contact on individual signals or data association operations, tend to be dependent on the content of the data. The overall structure of the goal hierarchy also will be affected indirectly by the mission objectives which are input to the top-level "Compile Sonar Picture" goal. Mission objectives will affect primarily the priorities given to processing different platform classes. Examples range from generic objectives involving non-specific platform categories, such as "rank military targets over non-military targets" or "rank subsurface targets over surface targets," to very specific objectives to track a specific platform class or even a specific vessel.

Control Structure

The control structure for goal-directed data integration consists of a sequence of four primary operations:

1. Goal monitoring;
2. Goal prioritization;
3. Plan generation and/or modification;
4. Plan execution and monitoring.

These operations are repeated after the receipt of each new data record from the sonar system.

The objective of goal monitoring is to identify those data integration goals which are not currently satisfied. These goals are defined to be *activated* and are placed in a queue for further processing. A goal may be activated directly by an external event or by a subgoal which is no longer satisfied. A previously activated goal may be *deactivated* by the successful execution of data integration operations specified in an associated plan or by the satisfaction of subgoals. Goal deactivation from subgoal satisfaction may occur when there is disjunctive relation between goals and subgoals. This is illustrated by the “Maintain Contact on Signal” and “Maintain Contact on Target” goals, as shown in Figure 2.

Activated goals are stored on a queue and assigned an initial priority based primarily on mission objectives and also on the level of the goal in the hierarchy. Mission objectives directly affect the priorities assigned to high-level tasks (classification, localization, threat assessment) for different vessel classes. In turn, task priorities are inherited by all subgoals of each respective high-level task. For example, given a scenario in which merchant surface vessels are of low interest, it may be sufficient to perform no localization and minimal classification (to the degree necessary to confirm a classification of merchant vs. non-merchant) on merchant

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[2] A parent goal is the inverse relation to the subgoal. If B is a subgoal of A, then A is a parent goal of B.

vessels. As a consequence, any activated goals in the localization subtree for a target classified as merchant will be assigned a low priority for further processing. Goal priorities based on mission objectives are adjusted according to the level of the goal in the hierarchy. In general, goals higher in the hierarchy are more critical to the tactical picture compilation task. Thus, an event which triggers a chain of goal activations up the goal hierarchy will receive a higher priority than an event which activates only a single bottom-level goal.

One restriction on goal prioritization, which has been introduced in order to minimize the number of activated goals stored on the goal queue, is that given two activated goals which are connected by an unbroken path of activated goals, only the highest goal in the hierarchy will be stored in the goal queue.

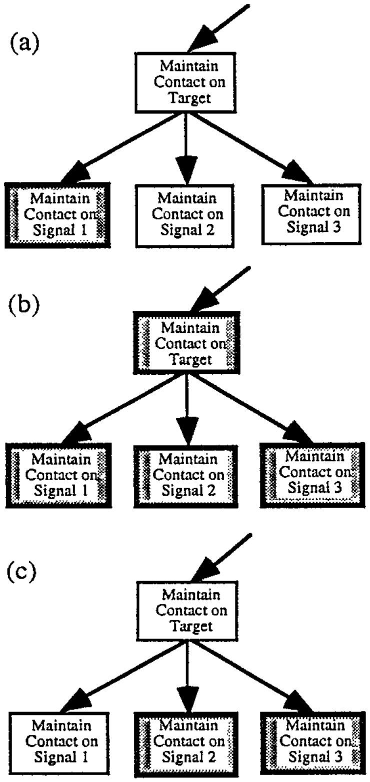


Figure 2. Goal activation and deactivation. Activated goals are shaded. (a) The goal "Maintain Contact on Signal 1" is activated by a loss-of-signal event. (b) The goal "Maintain Contact on Target" is activated only upon activation of "Maintain Contact on Signal" goals for all three signals. (c) Deactivation of goal "Maintain Contact on Signal 1" triggers the deactivation of the "Maintain Contact on Target" goal.

For each new goal added to the goal queue, a plan is generated for satisfying that goal. A plan consists of a sequence of one or more data integration operations. Plan generation is performed using goal-specific rules. Each candidate data integration operation is specified by a set of preconditions, implemented as rule antecedents. In cases where more than one operation is applicable, alternative plans may be generated using a backtracking process if an initially generated plan fails. Failure to match an association precondition may also trigger backward-chaining rules to initiate a search for additional data or to request assistance from the human operator.

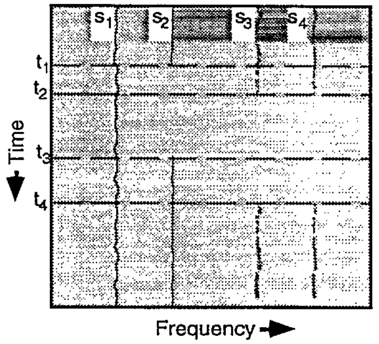
Given that the completion of individual plans may require extended periods of time, multiple plans are permitted to execute simultaneously. Plans execute with the priority assigned to their associated goals. In order to bound the resource requirements of the data integration system a fixed upper limit on the number of executing plans is assumed. When the limit on the maximum number of executing plans is exceeded, the lowest-priority plan may be suspended, temporarily or indefinitely. Goal priorities (and hence the priorities of associated plans) are modified during plan execution if the priority assigned to a high-level task changes. In addition, goal priorities may be decreased as the amount of time expended in executing associated plans increases.

Example: Fading Tracks Scenario. An example scenario involves the tracking of narrowband signals s_1 and s_2 from target c_1 and s_3 and s_4 from target c_2. A notional spectrogram of the four signals is shown in Figure 3(a). It is assumed that: signal trackers, producing a time sequence of frequency, bearing, and SNR measurements, are assigned to each of the four signals; intrasensor associations between s_1 and s_2 and between s_3 and s_4 have already been established; and, targets c_1 and c_2 have the same priority. Figures 3(b) and 3(c) outline the processing steps taken using the goal-directed approach when signal fades occur at times t_1 and t_2, respectively.

At time t_1 signal s_2 fades out. Shortly afterward a loss-of-signal event on signal s_2 is detected and goal g_1, "Maintain Contact on Signal s_2" is activated. Goal g_1 is the sole element of the goal queue and is selected for plan generation. Based on the criteria that the goal is to maintain contact on a signal, that activation of the goal was caused by a signal tracker loss-of-signal event, and that there is an associated signal, s_1, which is still being tracked successfully, a plan, p_1, is generated to reacquire signal s_2 by using a search cued from signal s_1. The search procedure uses bearing and frequency ratios between s_1 and s_2 established before the signal fade in combination with bearing and frequency measurements from s_1 to form a gate for identifying candidate detections from signal s_2. The search procedure is executed after the receipt of each new data record and with a priority equal to that of goal g_1.

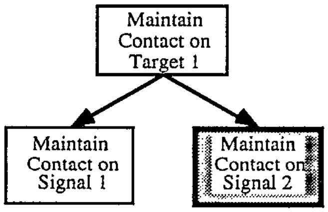
Loss-of-signal events on signals s_3 and s_4 are detected at a time shortly following t_2. This event results in direct activation of the bottom-level goals "Maintain Contact on Signal s_3" and "Maintain Contact on Signal s_4", and then the subsequent activation of the parent goal "Maintain Contact on Target c_2." Based on the rules limiting which goals are stored on the goal queue, a single goal; g_2, "Maintain Contact on Target c_2" is added to the goal queue. Goal g_2 has a higher priority than g_1 both because it arises from a higher level in the goal hierarchy and because it has been processed for a shorter period of time. The plan, p_2, generated for goal g_2, uses a search procedure specifically tailored for pairs of associated narrowband signals. This procedure, used successfully for regaining contact on narrowband signals following ownship manoeuvres [2], involves applying frequency and bearing constraints to identify candidate pairs of signal detections from s_3 and s_4. A multi-hypothesis search, using heuristic constraints on track smoothness, is used subsequently to identify sequences of candidate detections from the pair of faded signals. During the period between times t_2 and t_3, plan p_2 will be executed before plan p_1 because of its higher priority. In a situation where resource limitations would only allow for one of the two plans to execute, plan p_1 would be temporarily suspended.

(a)



(b) Time t_1

Goal Activation:
Goal g1: Maintain contact on signal 2



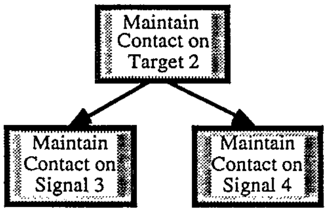
Goal Prioritization:
Goal queue: (g1)

Plan generation:
Plan p1: Reacquire signal 2 using cuing from signal 1

Rule:
If goal = maintain contact on signal &
cause = fading signal &
associated_NB_signal = TRUE
Then apply
Signal_Reacquisition_NB_cueing

(c) Time t_3

Goal Activation:
Goal g2: Maintain contact on target 2



Goal Prioritization:
Goal queue: (g2 g1)

Plan generation:
Plan p2: Reacquire target 2 using NB/NB association between signals 3 & 4

Rule:
If goal = maintain contact on target &
cause = fading signal &
 # NB signals > 1
Then apply
NB/NB_Signal_Pair_Reacquisition

Figure 3. Fading tracks scenario. (a) Narrowband display showing signals s_1 and s_2 from target c_1 and s_3 and s_4 from target c_2. (b) Goal processing at time t_1. (c) Goal processing at time t_2.

Operator-Machine Interface

Because it is assumed that ultimate responsibility for sonar picture compilation must reside with the sonar operator and the command team, goal-directed data integration is conceived as an operator aid rather than as a fully autonomous system. As such, the interface between the data integration system and the human operator is an important part of the overall design. Two operator-machine interface issues which have been given consideration to date are operator control of the data integration processing and communication of information to the operator.

The goal-based representation provides a natural user interface between the data integration system and human operator. A graphical display of the goal hierarchy structure and goal activation levels, similar to that shown in Figure 1, will provide visual feedback regarding the status of the tactical compilation task. The display should allow individual goals to be expanded and collapsed interactively to allow different portions of the tactical picture compilation task to be viewed at varying levels of detail. Additional operations should provide interactive display of goal attributes, including priority levels and associated plans, and allow examination of the goal queue.

An added benefit of the goal-based representation is that a graphical display of the goal hierarchy provides a rudimentary explanation capability. An explanation of the significance of a particular goal to the overall tactical picture compilation task is obtained by examining the parent goals. An explanation of how a particular goal is to be achieved is obtained by examining its subgoals. This basic capability could be extended to include explanations, in natural language format, for plans, based on the rule-based representation used for plan generation.

The primary means by which the operator is assumed to be able to control the operation of data integration processing is by assigning responsibility for processing specific goals to the system. For example, the operator might retain responsibility for handling all operations relating to mission-critical targets while assigning the system the task of monitoring goals for targets of secondary importance. Goals which are retained by the operator may also be monitored by the system. In the latter case, the system could alert the operator to goal activation but the operator would be responsible for taking corrective action. In all cases, the operator should be able to dynamically reassign responsibility for goals and set goal priorities through the graphical user interface. The operator should also be able to enter associations manually or be able to override associations proposed by the system.

4. SUMMARY

This paper has introduced a new framework, termed goal-directed data integration, for managing data integration operations in sonar picture compilation applications. The key concepts of this framework are a hierarchical goal-based representation for the sonar picture compilation task, and the use of a rule-based control structure for planning sequences of data integration operations. It has been proposed that the goal-directed framework can be more effective than conventional automated data integration frameworks because processing is focused on those signals and data integration operations which are necessary for solving problems which may arise during the compilation of the sonar picture.

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