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An Intelligent Reactive Controller for Ocean Science Autonomous Underwater Vehicles

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Final Report for Period: 08/1995 - 08/1998**Submitted on:** 10/21/1998**Principal Investigator:** Turner, Roy M.**Award ID:** 9696044**Organization:** University of Maine

An Intelligent Reactive Controller for Ocean Science Autonomous Underwater Vehicles

Participant Individuals**Senior Personnel****Name:** Turner, Roy**Worked for more than 160 Hours:** Yes**Contribution to Project:****Post-doc****Graduate Student****Name:** Dempsey, Martin**Worked for more than 160 Hours:** Yes**Contribution to Project:****Name:** Eaton, Peggy**Worked for more than 160 Hours:** Yes**Contribution to Project:**

This person worked on the project, but was not funded by the grant. (She was a Ph.D. student at UNH who was teaching there to support herself.)

Name: Ramakrishnan, Prabha**Worked for more than 160 Hours:** Yes**Contribution to Project:**

Prabha worked on an aspect of the Orca planner for her master's thesis project. For the demographic information, Prabha is Indian.

Undergraduate Student**Name:** Mailman, Jason**Worked for more than 160 Hours:** Yes**Contribution to Project:**

Jason worked on getting Orca to control a simulated AUV in the Navy Postgraduate School's Underwater Virtual World. I think he worked >160 hours, but he was also funded from another grant over the summer.

Name: Hall, Matthew**Worked for more than 160 Hours:** Yes**Contribution to Project:**

Matt worked on getting Orca to control a simulated AUV in the Navy Postgraduate School's Underwater Virtual World. Matt is continuing working with me for his senior thesis; he is now working on getting Orca to control a small land robot purchased in part with funds from this grant. I think he worked >160 hours; he was funded off another contract for part of the time, too.

Name: Drake, Justin**Worked for more than 160 Hours:** No**Contribution to Project:**

Justin worked on a simulator related to this project; he was investigating how to get Orca to control a simulated AUV in the Navy Postgraduate School's Underwater Virtual World.

Name: Matthias, Collette**Worked for more than 160 Hours:** Yes**Contribution to Project:**

Collette worked on a simulator used to test the work done in this project, as well as on software that was integrated into the Orca planner.

Partner Organizations

Autonomous Undersea Systems Institute

I have collaborated with AUSI (and its previous incarnation, the Marine Systems Engineering Laboratory) since before the inception of this project. Some grant funds were earmarked for collaborative purposes to go to MSEL/AUSI. I also worked with MSEL directly during part of the funding period, both at UNH and NEU. MSEL/AUSI provided and continues to provide domain knowledge and collaborative discussions on aspects of Orca.

Other Collaborators

I have discussed the project with colleagues at the Navy Postgraduate School (Don Brutzman, Tony Healey, and Bob McGhee) in relation to their work on autonomous underwater vehicle control. My goal is to control their Phoenix AUV, first in simulation and then ultimately the real thing, using the Orca program. Toward that end, we have been using one of their simulators (the Underwater Virtual World) here at UMaine.

A UNH Ph.D. student, Jamie Lawton, is being co-advised by Dr. Elise Turner and me, and his current project (opportunistic memory) interacts with and heavily relies upon Orca. Another NSF-funded project, IRI-9696055 (PI: Dr. Elise Turner), also interacts with Orca; Orca provides the intelligent controller within which the communications work in that project is done.

Due to work on this project in context-sensitive reasoning, I have begun an international collaboration with Dr. Patrick Brezillon (LIP 6, University of Paris) focusing on the explicit representation and use of contextual knowledge. Dr. Brezillon, Dr. E. Turner, Dr. J.-Ch. Pomerol have recently submitted a proposal to organize a workshop on context at IJCAI-99, and we have submitted a joint NSF/CNRS proposal to fund international collaboration on context.

Activities and Findings

Research Activities:

Most of the research activities performed during this grant period had to do with designing and implementing the Orca intelligent autonomous underwater vehicle (AUV) controller. This entailed a requirements analysis early in the project, followed by the design and implementation of the program. The latter two activities were interleaved; Orca was designed and implemented in a phased manner, with each new version of the program having more functionality. The current version is Orca 2.2. (For current information on Orca, see <http://cdps.umcs.maine.edu/Orca>.)

A large part of the effort centered on devising a knowledge representation for Orca so that the reasoner could represent facts about the underwater world, the AUV it controls, and itself, as well as knowledge about actions it knows how to do and situations it knows about. The latter two kinds of knowledge were represented as 'schemas', or packets of related knowledge, called respectively 'procedural schemas' (p-schemas) and 'contextual schemas' (c-schemas). Because of this representation format, Orca is a schema-based reasoner: all of its actions are governed by its schemas.

Work on fuzzy representation played a part in this project as well, especially in regard to representing contextual features.

Key activities during Orca's design and implementation focused on:

- o knowledge representation,
- o context-sensitive reasoning,
- o handling unanticipated events, and
- o finding and applying appropriate p-schemas to take action.

Context-sensitive reasoning has turned out to be a very important thrust of

this work.

Presentations were made in conjunction with the conference papers listed later in the report.

In addition to the work on Orca itself, ancillary work was done on creating and maintaining a simulation testbed for it and other projects. This simulator, SMART (Simulator for Multi-Agent Research and Testing), was begun before the grant period, but it was heavily revised and extended by the effort funded by this grant. SMART currently allows Orca to control simulated EAVE AUVs (AUVs that our collaborators at AUSI maintain). Three students, funded from another grant, are continuing this work and reworking SMART to be a distributed simulation testbed. (For information about SMART, see <http://cdps.umcs.maine.edu/Docs/smart/smart.html>.)

Work also took place on linking the Orca program to the Navy Postgraduate School's Underwater Virtual World simulator. The idea is to have Orca control its simulated Phoenix AUV as the first step toward having it control the Phoenix AUV itself. Work has continued on this after the grant period ended. Our goal for this is to have Orca, running at UMaine, control Phoenix in a test tank in Monterey via the Internet. We intend to seek funding for this project in the near future.

Research Findings:

Orca Design

The overall 'finding' was a design for Orca, shown in the attached PDF file (Figure 1: Design of the Orca schema-based AUV controller). The breakdown of the process of intelligent adaptive control into the modules shown is intuitive and has been effective in practice.

Event Handler (EH) manages the input from outside the program, which is assumed to be sensor data, possibly pre-processed, and messages from other agents or the user. EH watches for both anticipated events (i.e., those that ECHO or Schema Applier have predicted, possibly as a result of Orca's own actions) and unanticipated events. An example of the latter is power failure. Though it is not a novel event, in that it is a known kind of event, it is unanticipated in that it cannot be predicted when and under what situations it will occur. EH uses contextual information to determine when an unanticipated event has occurred and also to decide how important the event is and how to handle it.

Agenda Manager (AM) determines Orca's focus of attention. Sources of goals on the agenda are: the user's mission statement or later requests from the user or other agents; goals arising from EH's processing of unanticipated events; standing orders (see below); or goals explicitly generated as part of applying a p-schema. Attention is focused on the goal with the highest priority. This is determined with help from ECHO's contextual knowledge. When the situation changes, AM can change the focus of attention, which will interrupt Schema Applier.

Schema Applier (SA) is responsible for finding and applying a procedural schema (p-schema) to achieve the goal currently in focus. SA uses a least-commitment strategy for schema application. Schemas are only expanded as much as needed to find the next thing to do; commitment to future details are delayed as long as possible. This allows SA to find better p-schemas or actions to use to achieve the later steps based on its more accurate knowledge of the situation at the time the steps need to be carried out. In this, it is

like the Procedural Reasoning System (PRS) of Georgeff and colleagues.

Long-term memory (LTM) is a dynamic conceptual memory patterned after the memory in the MEDIC program (my dissertation work), which was in turn patterned after Kolodner's CYRUS memory system. Features of the situation are presented to the memory, which returns the schema or schemas that best fit the situation. LTM stores both p-schemas and c-schemas.

Working memory (WM) contains most of Orca's notion of what the current situation is. It is used for holding facts about the world. The current version has some very limited inference capability, for example, to update frames when predicate calculus-like facts are asserted and to retrieve answers to queries by looking in frames' slots. An earlier versions used resolution theorem proving for inferences.

The context manager, ECHO (Embedded Context Handling Object), is responsible for the rest of Orca's notion of what its situation is. It retrieves c-schemas from LTM that fit the situation, then merges them to create an overall picture of the context. This information is then used in several ways:

- o it provides EH with information about unanticipated events, including diagnostic knowledge, importance assessment information, and appropriate ways to handle them in the current situation;
- o it provides AM with information about the appropriate priority of goals in the current context;
- o it provides SA with starting points for searching for p-schemas, essentially giving it information about which p-schemas are appropriate for which goals in the context;
- o it provides all modules with situation-specific meanings of concepts, such as fuzzy linguistic values (e.g., 'too deep'); and
- o it sets a variety of parameters and activates goals as needed when in the current context; these are referred to collectively as 'standing orders'.

The above describes the design of Orca. The implementation status is as follows. Versions of SA, EH, LTM, WM, and AM exist, have been tested, and are in use by other projects, including one funded by NSF (grant number IRI-9696055). ECHO does not yet exist in its full form. Work on this module has continued after the grant period and will be the subject of a follow-on proposal in the near future.

Context-Mediated Behavior

A significant part of this work has been focused on the question of how an intelligent adaptive reasoner can reason in context: that is, how can its behavior be made to be context-sensitive?

Work on this has led to the development of a reasoning style called context-mediated behavior (CMB). The foundations of this work extend back to my dissertation work in medical diagnostic reasoning, but most of the work has been done in the Orca project. CMB takes the position that context should impact almost all facets of behavior, as noted above. Contextual knowledge, especially what it means for a reasoner to be in a particular context, should be explicitly represented, then retrieved and used as dictated by the situation. In Orca, such knowledge is represented as contextual schemas (c-schemas).

The idea that context should impact event handling, the focus of attention,

and schema application had its genesis in the earlier MEDIC project; it was refined during this grant. The idea of caching 'standing orders'--parameter settings and context-specific goals--in c-schemas and the idea of allowing concepts' meanings to change in context-specific ways were both direct outcomes of this grant.

In addition, the representation of c-schemas and how they are manipulated by ECHO came from this work. C-schemas are now seen as representing important facets of a context rather than necessarily representing an entire context. Several c-schemas can then be retrieved and merged to represent even novel contexts. For example, the situation of 'in a harbor, power is low, and performing a search mission' might be handled by ECHO retrieving c-schemas for 'in a harbor', 'low power', and 'search mission', then merging the information.

I expect work on context-mediated behavior to be one of my major research foci in the future. I believe it has implications for and applications to work far beyond AUV control.

P-schema Creation

One problem with schema-based reasoners is: what should be done when a p-schema cannot be found for a goal in the current situation? In this project, we have proposed a general answer to that question and have provided one particular implementation of the answer.

The answer we propose is that p-schemas be organized in a specialization hierarchy. When a specific p-schema, representing a particular way of achieving a goal, cannot be found, then the reasoner should fall back on less specific, but still applicable, p-schemas. This is an automatic property of the memory we use: the most specific p-schema for the situation is found.

At the top of the specialization hierarchy are the most general methods for achieving goals. These correspond to general problem-solving techniques, implemented as p-schemas. The advantage of this approach is that the reasoner automatically and transparently retrieves the best problem-solving method for the situation, assuming that its memory indexing is reasonable. New problem-solving methods, or special-purpose versions of existing ones, can be added to the memory and indexed according to the features of situations they are appropriate for.

One of my master's students worked on this as her thesis project. She implemented a version of Weld's Partial-Order Planner (POP) as a set of p-schemas and integrated their use into Orca. With her work in place, when no specific schema for a goal exists, Orca automatically retrieves a very high-level p-schema that corresponds to 'achieve a goal'. This schema then directs creates a plan for achieving the goal, then executes the plan. In earlier work in MEDIC, a similar idea was used to do a simple form of case-based reasoning.

Work on Orca in the future will focus on extending this problem-solving mechanism to other kinds of reasoning and on determining (possibly domain-independent) features of situations that should suggest particular forms of reasoning.

Event Handling

Work on event handling was an early and continuing focus in this project. We developed a model of unanticipated event handling that treats the problem as one of context-sensitive diagnosis. Features of the situation lead the context manager to provide context-dependent diagnostic knowledge, which the reasoner can then use to determine if an event has occurred, how important it is, and what to do about it.

The currently-implemented version is based on a fuzzy rule-based mechanism. A better model of this process was proposed (see the list of papers later in the report) that was based on Miller and Pople's work on the INTERNIST-I medical diagnostic program.

Working Memory

Much work has been done on knowledge representation and handling the interplay between Orca's primary knowledge representation formalism, frames, and the predicate calculus-like assertions that are most easy for working memory and other modules to deal with during some forms of reasoning (e.g., rule-based reasoning).

One outcome of this has been the identification of the need in our domain to extend the representation of objects to allow them to have temporal extent and to be able to represent different facts about them at different times. We are currently working on this as part of the work on context-mediated behavior, since such temporal representations are captured in part in contextual schemas.

Research Training:

The project has directly contributed to the research training of several students, including two Ph.D. students, an M.S. student, and several undergraduates. The two Ph.D. students were at the University of New Hampshire. Martin Dempsey worked on the project for about a year before leaving graduate school for personal reasons. It was his first exposure to research. Peggy Eaton worked on the project for about two years, but ultimately switched to another project on constraint-directed reasoning. Both Peggy and Martin worked on event handling in Orca, and they co-authored papers on the topic with me (see the list of publications later in the report).

Prabha Ramakrishan, a University of Maine M.S. student, did her master's thesis on the topic of adding partial-order planning to Orca. She co-authored a paper on the subject with me (see the list of publications).

Several undergraduates have worked on this project. Collette Matthias, a UNH undergraduate who later got her M.S. at UNH, worked on the SMART simulator to support Orca. Her M.S. project also interacted with this project; she used Orca as the basis of an inference mechanism to support understanding quantified expressions. Justin Drake, Matt Hall, and Jason Mailman, all UM undergraduates, worked on various aspects of connecting Orca to the Navy Postgraduate School's Underwater Virtual World simulator. Matt is currently continuing this topic, as well as connecting Orca to a small land robot at UM, as his senior thesis.

The project has indirectly contributed to the research training of several other students. John Phelps, an undergraduate who is working on another

NSF-funded project (IRI-9696055), uses Orca in his project. Three undergraduates students in UM's COS 470 (Introduction to Artificial Intelligence) class are currently working on Orca's context-sensitive reasoning mechanism with me as their class project. Jamie Lawton, a UNH Ph.D. student whom I co-advise, is interacting heavily with Orca for his current project. In fact, the opportunistic memory he is currently working on is based on Orca's long-term memory.

Education and Outreach:

I use Orca as an example in my artificial intelligence and other classes as appropriate. I also discuss Orca when talking about my research to incoming first-year students.

Journal Publications

Roy M. Turner, "Context-mediated behavior for intelligent agents", *International Journal of Human-Computer Studies*, p. 307, vol. 48, (1998).) Published

Roy M. Turner, Peggy S. Eaton, and Martin J. Dempsey, "Handling unanticipated events in single and multiple AUV systems", *l'Onde Electrique (Revue de la Societe des Electriciens et des Electroniciens)*, p. 36, vol. 74, (1994).) Published

Books or Other One-time Publications

Roy M. Turner, "Adaptive Reasoning for Real-World Problems: A Schema-Based Approach", (1994). *Book*, Published
Bibliography: Lawrence
Erlbaum Associates, Inc., Hillsdale, NJ

Roy M. Turner, "Context-mediated behavior", (1998). *conference paper/in collection*, Published
Bibliography: Lecture Notes in Artificial Intelligence 1415: Proc. 11th Int. Conf. on Industrial and Eng. Appl. of Art. Intell. and Expert Systems, Benicassim, Spain (Springer: New York)

Prabha Ramakrishnan and Roy M. Turner, "Integrating partial-order planning into the Orca schema-based mission controller", (1997). *conference/symposium*, Published
Bibliography: Proceedings of the 10th
International Symposium on Unmanned Untethered Submersible Technology (UUST), September, 1997, pp. 416--425

Roy Turner, "Determining the context-dependent meaning of fuzzy subsets", (1997). *conference*, Published
Bibliography: Proceedings of
the 1997 International and Interdisciplinary Conference on Modeling and Using
Context (CONTEXT-97), Rio de Janeiro, February 4-6, 1997, pp. 233-242

Roy Turner, "Intelligent control of autonomous underwater vehicles: The Orca project", (1995). *conference*, Published
Bibliography: Proceedings of the 1995 IEEE International Conference on Systems, Man, and
Cybernetics, Vancouver, Canada, October, 1995.

Roy M. Turner, "Context-sensitive, adaptive reasoning for intelligent AUV control: Orca project update", (1995). *conference/symposium*, Published
Bibliography: Proceedings of the 9th International Symposium on Unmanned
Untethered Submersible Technology, Durham, NH, September, 1995, pp. 426-435.

Roy M. Turner and Peggy S. Eaton, "Handling unanticipated events during collaboration", (1994). *conference*, Published
Bibliography: Proceedings of the Sixteenth Annual Conference of the
Cognitive Science Society, Atlanta, GA, 1994, pp. 887-892

Roy M. Turner, Peggy S. Eaton, and Martin J. Dempsey, "Handling unanticipated events in single and multiple AUV systems", (1994). *conference*, Published

Bibliography: Proceedings of the IEEE Oceanic Engineering Society Conference (OCEANS '94), pp. II-125- 130, Brest, France, 1994

Web/Internet Sites

None

Other Specific Products

Product Type: Software (or netware)

Product Description:

The Orca program, an intelligent controller, was developed with support from this grant. The program is in use by other projects here at UM, including another NSF-funded project (IRI-9696055).

Sharing Information:

The software is shared with others on an as-needed, as-is basis. We hope in future to make versions of Orca available to the general AUV community as research software; however, the current state of the program is not such that it would support that at this time.

Contributions

Contributions within Discipline:

The work funded by this grant has made several contributions to the computer science sub-field of artificial intelligence (AI). Overall, the work has developed a mechanism for the intelligent control of autonomous agents. The kind of agents focused on during the grant period was autonomous underwater vehicles (AUVs). AUV control is a challenging domain due to the high uncertainty involved in the knowledge about the ocean, the poor sensors available, the nature of the hardware being controlled, and the dynamic nature of the world. The mechanism developed and refined by this work, schema-based reasoning (SBR), is useful for agent control in such domains. It encompasses mechanisms for handling unanticipated events, for dynamically focusing attention on goals that are the most important, and for context-sensitive behavior. Our work has applicability to other autonomous agent domains, including controlling other kinds of robots and autonomous software agents (e.g., on the Web). The work on context-sensitive reasoning has application to any reasoning system that operates in different contexts.

The context-sensitive reasoning work is perhaps the most important contribution of the work to the field. This work culminated in an approach called context-mediated behavior (CMB) that allows a reasoner to automatically adjust its behavior to fit its context. The basis of CMB is the explicit representation of contexts and contextual knowledge, something that has in general received little attention in AI other than in the logic community. The work on this project in that area is among some of the first work done anywhere on using explicit representations of context in real-world systems. The work has been well received in the nascent international and interdisciplinary context community.

One of the unique aspects of CMB is its ability to represent a concept's different meaning in different situations. This was demonstrated in Orca by using fuzzy knowledge as an example. In that case, the membership function corresponding to a linguistic value (e.g., 'too deep') was provided by contextual knowledge contained in c-schemas. The appropriate membership function for the context was retrieved and used, modifying the agent's behavior appropriately. This technique should also work for other kinds of

reasoners; for example, a neural network could be coupled with a context manager that would give it appropriate weights for different contexts in which it finds itself.

We have also developed an approach to seamlessly integrating general reasoning methods with ones that are highly-specific for a particular situation. SBR allows general reasoning methods, such as planning or case-based reasoning, to be implemented as procedural schemas. If more specific techniques cannot be found, then the reasoner will automatically retrieve and use these general-purpose methods to solve the problem.

With respect to event handling, we have proposed an approach based on work in medical diagnostic reasoning to identify the unanticipated events that have occurred. Context-dependent information is provided by Orca's context manager to help identify events and diagnose, assess, and handle them in a way most appropriate for the current situation.

Contributions to Other Disciplines:

The other discipline that this work most affected is ocean engineering, in particular autonomous underwater vehicle (AUV) control. Over the course of this grant, I have been heavily involved in the AUV community, presenting at international conferences and symposia, working with one of the major AUV labs (AUSI), and visiting and beginning to establish collaborative ties with other labs. Orca, and the techniques developed in this project for AUV control, are widely known in the AUV community. As one of the few AI researchers active in this field, my participation at conferences and symposia has served in a small way to bring to the attention of AUV researchers issues in high-level mission control. In particular, the work on Orca is one of the few projects in the AUV community that heavily focuses on the need for context-sensitive reasoning.

Contributions to Education and Human Resources:

Work on this project has helped train several undergraduate and graduate students, as discussed previously. As a project focusing on a 'flashy' domain, the project has indirectly contributed to the research-related education of students here and at UNH by attracting them to work with our research group. With respect to diversity, the project has employed two women, one of whom was an international student.

Contributions to Science and Technology Infrastructure:

Beyond Science and Engineering:

The project has had little direct impact beyond science and engineering yet. However, technology developed during the project period and beyond will likely contribute to several areas of society. AUVs are likely to become increasingly important for such things as environmental monitoring (especially global change monitoring, ground truthing satellite data, etc.), industry (e.g., mariculture applications, fisheries management, ship hull inspection, etc.), and the military. As AUVs come into more common use, they will need intelligent controllers. This project contributes toward addressing that need. The techniques developed also have application to other kinds of intelligent agents. One kind that is likely to be increasingly important is the software agent ('knowbot', 'softbot', Web agent, etc.). Techniques from Orca should be applicable to these types of agents as well.

Categories for which nothing is reported:

Any Web/Internet Site

Contributions: To Any Science or Technology Infrastructure