A&QT-R 2002 (THETA 13)
2002 IEEE-TTTC - International Conference on Automation, Quality and Testing, Robotics
May 23 – 25, 2002, Cluj-Napoca, Romania

CONTROL ARCHITECTURE EXTENSION FOR AN AUTONOMOUS UNDERWATER VEHICLE EMPLOYING A SUBSUMPTION APPROACH

Levente Molnar, Trevor Love, Daniel Toal and Colin Flanagan

University of Limerick, Dept. Electronics and Computer Engineering, Limerick, Ireland
Levente.Molnar@ul.ie; Trevor.Love@ul.ie; Daniel.Toal@ul.ie; Colin.Flanagan@ul.ie

ABSTRACT
The paper describes the design and implementation of an intelligent, autonomous, undersea robot. The robot will be capable of surviving and operating in the open sea and will not need detailed instructions from a human operator in order to carry out its assigned task of marine inspection. The Autonomous Underwater Vehicle (AUV) employs subsumption architecture for control with a priority based arbitration mechanism. A modified version of the subsumption approach has already been implemented successfully on a land based experimental robot. We wish to reuse and extend the controller development, to endow the submersible robot with obstacle avoidance capabilities, destination seeking, navigation, environment exploration, depth and buoyancy control among other behaviours. The subsumption architecture approach employed equips the AUV with the intelligence needed to allow it to survive when the operating environment changes in ways that cannot be predicted in detail, a priori, by the builder.

KEYWORDS
Autonomous Underwater Vehicle; Subsumption Architecture

1. INTRODUCTION

The predecessor of the Autonomous Underwater Vehicle (AUV) under discussion in this paper is a land based robot built by the authors [1]. The robot uses an enhanced version of Brooks's Subsumption Architecture [2] for control, with fuzzy logic employed for command arbitration [3]. Low level behaviours, (Wandering, Light Following and Obstacle Avoidance), developed on the land based robot form the implementation framework for other higher level behaviours. These three low level behaviours illustrate the robot's capability to react directly to sensor stimuli, and perform seemingly intelligent tasks by their mutual interaction. To allow the robot to explore and map its environment, another set of behaviours, namely: Search for Edge, Edge Following, Landmark Detection, Mapping, Localisation and Navigation, were developed [1]. The Mapping and Navigation behaviours interact and communicate with each other using a blackboard. The blackboard helps to alleviate one of the shortcomings of standard behaviour based systems, i.e., the sharing of knowledge and system states. An arbitration function has been used giving control over the motors by the simultaneously attending behaviours according to their relative importance.

2. BACKGROUND

The subsumption architecture was developed by Rodney Brooks at the Massachusetts Institute of Technology. Brooks argued that building world models and reasoning using explicit symbolic representational knowledge was an impediment to timely robotic response. The subsumption approach tackles the control problem as a number of horizontally arranged layers, each layer implementing a "behaviour", i.e., the ability to perform a certain task. The name "subsumption" arises from the coordination process used between the layered behaviours within the architecture. In the subsumption architecture complex actions subsume simpler behaviours [2]. A priority hierarchy fixes the topology.

Advantages of the subsumption architecture include flexibility, robustness, and low computational overhead, allowing a robot to exhibit true dynamic reactive behaviour. Disadvantages include difficult synchronization and timing between behaviours, complexity of the system with large number of behaviours, and a lack of high level control [4]. Variations on the subsumption idea have been used in autonomous undersea vehicles, with the Odyssey II and Sea Squirt being notable examples. Both of these vehicles have employed a modified subsumption architecture, the "state configured layered control" [4]. The Sea Squirt employs a planning and control architecture for providing intelligent capabilities. The mission planning system [5], which generates the required heading, speed and depth commands to guide the AUV, is based on the layered control architecture developed by Brooks. This layered control system is broken into "reflexive" modules where communication between behaviours is not allowed. When behaviours generate conflicting commands, conflict is resolved using a fixed prioritization scheme [6]. The layered control work previously developed on Odyssey I and on the Sea Squirt has been substantially improved and implemented on Odyssey II. An important feature of Odyssey II control software is the vehicle state structure which contains description and values for sensors and behaviours. It also contains the configuration of the active layered control structure (i.e. the priority and argument values for active behaviours) and the output command structure [7].

3. ROBOT HARDWARE DESIGN

The design of the robot under discussion here has been described by Toal et. al. [8]. The electronic control hardware is designed in the form of a distributed control architecture, in which a number of separate modules are being used to perform complex tasks. The advantage of distributing the workload to different modules is that it frees the main processor or controller from performing repetitive albeit complex time-consuming tasks. The distributed control architecture has already been implemented on land based robots [1], [9]. The module used as central controller, is the CM/P5e, an embedded Pentium CPU module from Ampro Computers. The processor runs at 166 MHz and has 32 MB of RAM and 8 MB storage capacity "Disk On Chip". Two system expansion buses, PCI and ISA offer in system integration flexibility. The control software development is in C++, and will run under the preemptive, real-time multitasking operating system MicroC/OS-II.

Propulsion is provided by trolling motors manufactured by MinnKota. These motors are designed for use as electric boat out board trolling motors, and have been used successfully for shallow submersible operation [10]. The AUV (illustrated in figure 1) depth rating can be increased at a later stage by replacing the trolling motors with fully sea hardened sub-sea motors but at significant cost.

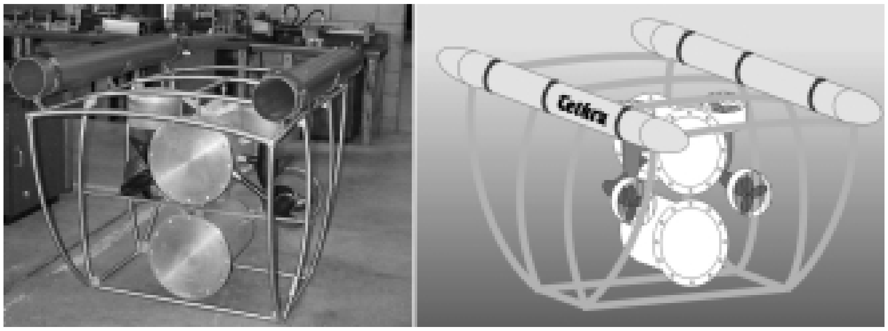

Figure 1 Photograph and computer aided drawing of the AUV.

The buoyancy control is realised using a variable ballast system. This system allows neutral buoyancy control at any design depth and also allows the craft to carry out controlled dives and surfacing from depth under fault conditions. The system incorporates 4 ballast tanks, which have a combined volume of 8 litres, giving the craft a maximum variable ballast of approximately 8.2 kilograms in seawater. The amount of ballast in the tanks is controlled using pressurized air from a standard scuba-diving air tank. To increase ballast, water is allowed to flood the tanks and air is vented. To decrease ballast the supply of pressurized air is used to force water from the tanks. The flow of air is controlled using two 24 volt solenoid operated uni-directional valves. The flow of water is controlled using a single bi-directional 24 volt electrically actuated ball valve. When the required amount of ballast is achieved the tanks are sealed off. A differential pressure transducer is used to measure the differential pressure between the ballast tanks and the outside environment. If pressure differential is above a certain limit, due to the craft changing depth from that at which ballast was set and sealed off, the ballast control function is modified. With a differential pressure above 1 bar as monitored by the differential pressure transducer, the internal ballast tank pressure is equalised to the outside ambient pressure by adding or venting air before the bi-directional water valve is operated. This is done to make the craft safer and ensure the effectiveness of neutral buoyancy control at greater depths.

For launch and retrieval and also for overriding the autonomous onboard controller during testing a radio controller is encorporated. The radio controller is also involved in the control of the buoyancy/ballast for positive–neutral–negative buoyancy at launch prior to switch to autonomous mode. The submersible thrust drives, buoyancy control and control surfaces are integrated with the onboard CPU/controller and the radio controller through an analogue switch. This analogue switch is in turn controlled by the radio controller thus providing radio control and human operator override.

For autonomous operation the AUV must detect obstacles in its path and have the capability of manoeuvring to avoid them. This is achieved using echolocation or sonar, transmitting ultrasonic pulses in water and measuring distances in terms of the time for the echo pulse to return. In the case of the AUV under development the sonar system must cover the three-dimensional environment of the submersible and the most appropriate system for this purpose is being investigated. The primary obstacle avoidance requirement is met with an array of simple directional sensors, used to detect any obstacle within a critical distance of the robot thus allowing the robot to react appropriately. Bottom placed sonar sensors provide altitude information. Scanning or profiling sonar sensors will be integrated at a later stage and used by higher level behaviour based competencies to allow the robot to map out its immediate environment in more detail.

Experiments are ongoing on a small AUV test model with specific heading and pressure/depth sensors [11]. The direction-heading sensor used is the Vector 2x Compass module. The depth sensing capability is realised using the Honeywell 40PC pressure sensor. These sensor systems will be implemented on the AUV described in this paper once debugged on the small test AUV.

4. CONTROL SOFTWARE EXTENSION

The AUV is being realised by porting, improving and thoroughly developing the subsumption control approaches from the land based robot to the autonomous underwater vehicle. In an early stage by using the land based robot’s control software development on the AUV operating on the water surface in a controlled environment, we will achieve the ability to control the sonar and a pair of thrusters. We can thus control the AUV as an ASV (autonomous surface vehicle). Important, further tasks include 1) the adaptation to the three-dimensional environment endowing the robot with controlled motion for the vertically oriented thrusters and 2) the control of buoyancy/ballast for positive - neutral - negative buoyancy.

The following behaviours were implemented on the land based robot: Wandering, Light Following, Obstacle Avoidance, Search for Edge, Edge Following, Landmark Detection, Mapping, Localisation and Navigation behaviours [1]. Several of these map onto behaviours meaningful to the AUV. At the most fundamental level, the AUV on the water surface will be able to move in horizontal plane, straight ahead due to the Cruise behaviour and will avoid obstacles in its path using the Obstacle Avoidance behaviour. For testing the AUV in a controlled environment, such as a pool, the Search for Edge behaviour locks the vehicle onto an edge, ensuring that it is parallel to it. The Edge Following behaviour then causes the vehicle to travel parallel to the edge at a certain predefined distance. The Landmark Detection behaviour turns the vehicle if a convex or concave corner is detected. The block diagram of the control architecture for testing in controlled environment is shown in figure 2.

The next step will be the adaptation to the three-dimensional environment endowing the robot with controlled motion for the vertically oriented thrusters. Implementing a “Maintain Altitude” behaviour, similar to the one employed on the Oberon submersible robotic vehicle [12], allows our robot to maintain a predefined distance above the sea floor in order to record on videotape the target mission.

Downward oriented sonar was used on Oberon to determine the altitude of the robot. The difference between the desired and actual altitudes determines the amount by which this behaviour would like to change depth [12]. This difference is subtracted from the current measured depth to set a new desired depth. The “Maintain Depth” behaviour allows our robot to maintain a certain predefined depth as specified by the programmed mission.

On our AUV the horizontally positioned sonars are involved in avoiding collisions. Bottom placed, downward oriented sonars provide information for maintaining altitude. The pressure sensor provides information for the Maintain Depth behaviour as well. Both the Maintain Altitude behaviour and the Edge Following behaviour implemented on the AUV are used for maintaining a certain predefined distance of the robot motion from outline of features in their environment. For implementation of the “Maintain Altitude” behaviour and “Search for Bottom” behaviour the land based robot's Edge Following and Search For Edge behaviours code is being adapted. The “Following Cardinal Points” behaviour process heading information to maintain the heading to predefined, different cardinal points for certain distances.

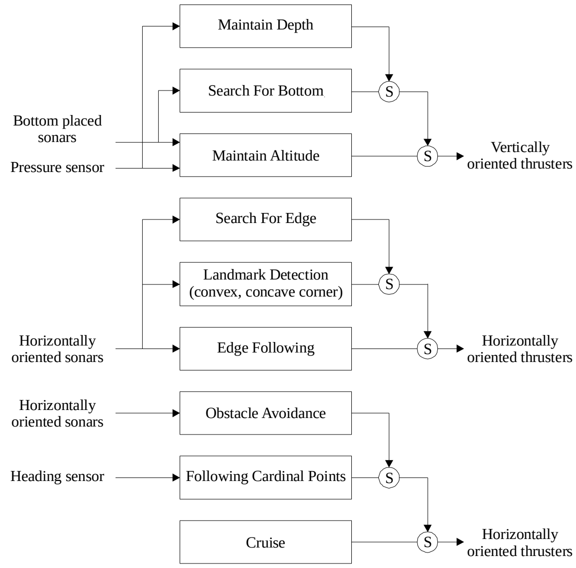

Figure 2 Block diagram of the control architecture for testing in controlled environment

The Mapping, Navigation and Destination Seeking behaviours will endow the vehicle with the ability to build up a map and to explore its environment. Localisation behaviour will be used for ascertaining the vehicle position with regard to the built global map.

A Fail Safe behaviour monitors for systems safety by the use of water leak and temperature sensors within the electronic housings and battery voltage sensor. Under fault conditions it will trigger the ballast tanks for a controlled surface.

In behaviour based architectures a number of behaviours run concurrently. Many of these behaviours can all send commands to the actuators at the same time. To prevent a conflict from occurring an arbitration function has to be implemented. The arbitration function has to select a single behavioural response from a multitude of possible ones. Each of the behaviours is layered according to their relative importance. It continuously monitors the output from each behaviour and using a fixed priority hierarchy, selects one single output to send to the thrusters. The Obstacle Avoidance behaviour is able to subsume the output of both the Following Cardinal Points behaviour and the Cruise behaviour when an obstacle lies in the vehicle's path. Similarly the Following Cardinal Points behaviour can subsume the output of the Cruise behaviour.

An important difficulty encountered in our robot software migration would be the adaptation to the three-dimensional environment. The land based robot has only three degrees of freedom, being able for translation in the ground plane and rotation around its central axis. The AUV is capable of surge, heave, yaw and roll manoeuvres. It has four degrees of freedom not being able to perform lateral motion and pitch, thus it is non-holonomic. Two horizontally and two vertically placed thrusters endows the AUV with controlled motions in both horizontal and vertical planes. The Maintain Altitude and Maintain Depth behaviours allows to keep a certain predefined distance above the sea floor or to maintain a certain desired depth, thus will control translations in vertical plane.

5. CONCLUSIONS

As described above the subsumption approach was already implemented on the land based experimental robot. We are currently reusing and extending the controller development to endow the submersible robot with obstacle avoidance capabilities, destination seeking, navigation, environment exploration, depth and buoyancy control among other behaviours.

We have implemented a hybrid radio controlled / autonomous mini-sub. As a preliminary result we have achieved a radio controlled submersible vehicle. Propulsion tests for autonomous mode in controlled environment are ongoing. The next major step is to endow it with autonomous control based on the subsumption architecture. In conclusion we have described the porting and extension of the control development of a land based robot to our autonomous underwater vehicle.

REFERENCES

[1] Leyden, M., Toal, D., Flanagan, C. (2000), An Autonomous Mobile Robot Built to Investigate Behaviour Based Control, The 7th Mechatronics Forum International Conference, Atlanta, Georgia, USA.

[2] Brooks, R. A. (1999), Cambrian Intelligence – The Early History of a New AI, MIT Press, Cambridge, London, England, Pages: 3-27.

[3] Leyden, M., Toal, D., Flanagan, C. (1999), A Fuzzy Logic Based Navigation System for a Mobile Robot, Automatisierungssymposium, Wismar.

[4] Valavanis, K.P., Gracanin, D., Matijasevic, M., Kolluru, R., Demetriou, G.A. (1997), Control Architectures for Autonomous Underwater Vehicles, *IEEE Control Systems Magazine* , Volume: 17, Issue: 6 , Pages: 48-64.

[5] Loch, J., Wallar, E., Bellingham, J.G., Beaton, R., Triantafyllou, M. (1989), Software Development for the Autonomous Submersible Program at MIT Sea Grant and Draper Laboratory, *Proceedings of the 6th International Symposium on Unmanned Untethered Submersible Technology*, Pages: 25 -32.

[6] Bellingham, J.G., Consi, T.R., Beaton, R.M., Hall, W. (1990), Keeping layered control simple, *Proceedings of the Autonomous Underwater Vehicle Technology*, Pages:3-8

[7] Bellingham, J.G., Goudey, C.A., Consi, T.R., Bales, J.W., Atwood, D.K., Leonard, J.J., Chryssostomidis, C. (1994), A second generation survey AUV, *Proceedings of the Autonomous Underwater Vehicle Technology*, Pages: 148 -155.

[8] Toal D., Flanagan C., Molnar L., Hanrahan G. (2001), Autonomous Submersible Development for Underwater Filming Employing Adaptive Artificial Intelligence, *Sensors and Their Applications XI*, London, England, Pages: 163-168.

[9] Toal D., Flanagan C., Jones C., Strunz B. (1996), Subsumption Architecture for the Control of Robots, Proceedings IMC-13, Limerick, Ireland.

[10] Gaskett C., Wettergreen D., and Zelinsky A. (1999), Reinforcement Learning applied to the control of an Autonomous Underwater Vehicle, *Proceedings of Australian Conference on Robotics and Automation ACRA'99*, Brisbane, Australia.

[11] Nolan S., Toal D., Flanagan C. (2002), Evolving Miniature Robots for the Underwater Environment, The 8th Mechatronics Forum International Conference, Twente, Enschede, Netherlands.

[12] Rosenblatt J., Williams S., Durrant-Whyte H.F. (2000), Behavior-Based Control for Autonomous Underwater Exploration, IEEE International Conference on Robotics and Automation, San Francisco CA, USA.