Autonomous Transect Surveying of the Great Barrier Reef

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Abstract

This paper presents work done as a step towards fully autonomous navigation using the Oberon submersible developed at the University of Sydney. The Oberon team is currently working on a project proposed by the Australian Institute of Marine Sciences (AIMS). This organisation is surveying sections of the Great Barrier Reef in order to study the growth and propagation of coral. They send a diver to record video transects of the reef while holding an underwater video camera at a height of approximately 30cm above the coral. The video images are then analysed to determine the growth and density of various coral structures. This presents an ideal opportunity for the introduction of a small, submersible robot to perform the data collection task with some degree of autonomy. The task has been divided into two sub-tasks: maintaining altitude above the reef and following the linear transect. Independent behaviours and decoupled controllers provide a modular means of accomplishing these tasks. Both a sonar-based approach and vision are being considered as methods with which to guide the robot along its intended course.

Introduction

Keeping a scientifically rigorous track of change on the Great Barrier Reef is an essential component of good reef management. The Great Barrier Reef survey project of the Australian Institute of Marine Sciences (AIMS), initiated in 1991, is designed to provide long-term quantitative geographic data about corals, algae and marine life over the extent of the Great Barrier Reef. This data is an information source for the Great Barrier Reef Marine Park Authority as well as a basis for studies of abundance and population change in selected organisms on a large geographic scale.

AIMS divers are currently required to perform broadscale surveys of coral densities and censuses of corals and marine life that form the basis for status reports. A set of reefs is monitored on an annual basis; others are sampled when specific issues arise. Currently, visual transect information is recorded using underwater video cameras held above the reef as the diver follows a prescribed path (Figure 1). Subsequent analysis of the recorded sequences is used to determine coral diversity and growth patterns. This project presents an interesting opportunity for the introduction of a small, autonomous subsea robot to perform the reef-surveying task.

Figure 1 - Diver taking a visual transect of the reef

In order to achieve some level of autonomous control of a robotic vehicle the context in which the robot will be used must be well understood. The environment in which it will operate and the tasks that it will be required to undertake will all impact heavily on the sensors and control schemes that are adopted.

In the early development of any robotic system, it is important to find tasks that are achievable and at the same time provide enough complexity to be interesting. The task that has been proposed by the AIMS group has proven to be an ideal one with which to begin work towards a truly autonomous submersible robot. It provides few restrictions on the method with which the task will be accomplished but sets clear goals to be achieved.

The task itself can be divided up into two distinct problems that must be solved – maintaining a fixed height above the reef and traversing the linear transect. Separate behaviours and controllers are used to develop and accomplish each of these sub-tasks independently. It must have a stand-off behaviour that allows it to maintain a fixed altitude above the reef while it follows the transect and collects data for later off-line analysis.

The robot must also have the ability to traverse the section of reef in a straight line and to be able to repeat its path on subsequent missions. Without absolute position data available to the sub, it is necessary to sense features in the environment and to deduce the vehicle's position from these features. There are a number of ways in which this could be accomplished and two methods are currently being pursued – visual servoing on a line laid out along the coral and using sonar to navigate relative to targets mounted along the line.

By decoupling the control into the separate subproblems of altitude control and line following, the individual controller design is greatly simplified. The behaviours to be exhibited by the robot can be developed independently of one another and later combined to allow the robot to meet its goals.

The Oberon Vehicle

The AUV project at the University of Sydney has focused on the development of a mid-size submersible robotic vehicle called Oberon (Figure 2). This device is intended primarily as a research platform upon which to test a variety of sensing strategies and control methods.

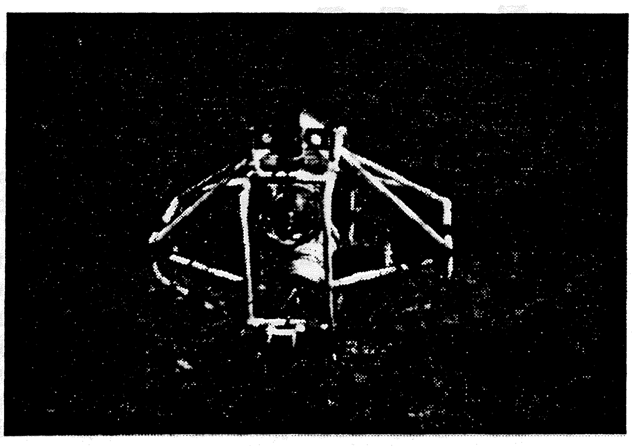

Figure 2 – the Oberon vehicle

Embedded controller

At the heart of the control of the robot is an embedded control system. At the time of the experiments reported here, the Oberon vehicle was controlled using a series of transputers. The Oberon robot has since been upgraded to use a CompactPCI system running Windows NT that interfaces directly to the hardware and is used to control the motion of the robot and to acquire the sensor data. This data is collated and sent to the surface where a network of computers are used for further data processing and to display the information to provide the user with feedback about the state of the sub.

A number of processes have been developed to accomplish the tasks of gathering data from the robot's sensors, processing this data and reasoning about the course of action to be taken by the robot. These processes communicate asynchronously via a TCP/IP socket-based interface.

Communications between the computers at the surface and the sub are via a tether. This tether also provides power to the robot, a video cable for transmitting video data and a serial line for control of the camera pan/tilt unit. While some effort might have been spent on eliminating the tether, it was felt that the development of the navigational techniques was of more immediate interest.

Sonar

Sonar is the primary sensor of interest for the Oberon project. Navigating autonomously underwater using these sonar sensors is one of the ultimate goals of the project [Newman and Durrant-Whyte, 1997]. There are currently two sonars on the robot.

An Imagenex sonar unit has been mounted at the front of the vehicle. It is positioned such that its scanning head can be used as a forward and downward looking beam. This enables the altitude above the sea floor as well as the proximity of obstacles to be determined using the wide beam of the sonar.

The second sonar is a Tritech SeaKing. This sonar has two narrow beam sonar heads and is considerably faster than the Imagenex unit. It is mounted on top of the sub and is used to scan the environment in which the sub is operating. It can achieve 360° scan rates on the order of 0.25 Hz. The information that is returned from this sonar is used to maintain a feature map of the environment.

Internal Sensors

A pressure sensor is used to measure the depth of the sub below the surface of the ocean. This sensor provides a voltage signal proportional to the pressure and is sampled at high speeds by an analogue to digital converter on the embedded controller. This sensor is used to control the depth of the sub.

An Andrews Laser Gyro has been included in the Oberon robot to allow the robot's orientation to be determined. This sensor provides fairly accurate heading information and is used to control the heading of the sub.

A tri-axial, Crossbow accelerometer is also present. Since the Oberon is a relatively slow-moving vehicle, this is used primarily as a tilt sensor. The accelerations experienced by the sub are negligible and the accelerometers can be used to measure the inclination of the sub relative to the gravitational field.

Camera

A small Pulnix camera is used to provide video feedback of the underwater scenes in which the robot operates. This is a colour camera and sends the video signal to the surface via the tether. A Matrox Meteor card is then used to acquire the video signal for further image processing.

Thrusters

There are currently 5 thrusters on the Oberon vehicle. Three of these are oriented in the vertical direction while the remaining two are directed horizontally. This gives the vehicle the ability to move itself up and down, control its yaw, pitch and roll and move forwards and backwards. Side to side motion is not possible with this thruster arrangement.

Solving the Problem

Maintaining Altitude above Sea Floor

The first task that must be accomplished in order to realise the goals set out in this project is the ability to maintain the robot at a certain altitude above the sea floor. The robot must be able to detect the ground and maintain its height in order to avoid colliding with the coral specimens (Figure 3).

This task has been accomplished using a combination of the Imagenex Sonar and the depth sensor. The robot maintains a particular depth using a simple PID controller based on the measurements returned by the depth sensor. The Sonar is then used to periodically determine the desired depth by finding the altitude of the robot.

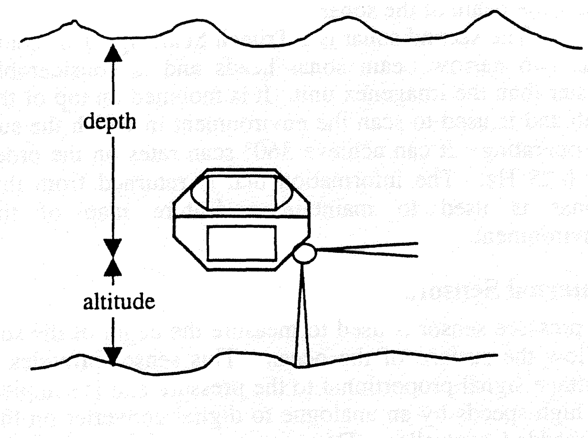

Figure 3 - Maintaining altitude above sea floor

By coupling the depth controller with the depth sensor, which is continuously sampling the depth, the sub can quickly respond to disturbances in its depth. The Imagenex sonar operates at a much slower rate (on the order of 5 Hz) and would be unable to supply the information at a rate sufficiently high to reject these disturbances. However, it is well suited to the task of setting the desired depth for the sub to maintain.

This approach allows the Imagenex sonar to be shared by both the task that maintains the altitude of the sub and by tasks interested in obstacle avoidance. Since the resources of any robot will be limited, it important to share these resources as necessary. A task scheduler has been implemented that allows resources to be shared between various tasks based on their relative priority.

Line Following

The robot must also have the ability to follow transect survey path. At present, this line consists of a white measuring tape that is draped along the coral that the diver follows during a survey. The robot is required to follow a straight line in order to survey the same section of the reef during each pass. We are currently investigating two different approaches to following the line.

Visual Servoing of the Line

The first approach uses the camera in order to accomplish this task. A line tracker has been implemented that uses the colour of the line to track it through the coral (Figure 4). It searches the image for pixels that match a certain RGB value to within a variable threshold [Ballard and Brown, 1982; Gonzalez and Woods, 1993]. The user can set this threshold value and the settings will depend on the lighting conditions that exist during the test. The initial RGB value is set by the user clicking on the object of interest, and is automatically updated to adapt to changing imaging conditions.

The x-y coordinates of the i[th] pixel (x_i, y_i) found are then fitted to a straight line using a linear regression algorithm (Equation 1). This provides a reasonable approximation to the line that is being tracked. A median filter can be used to increase the reliability of the line fit by rejecting outlying points matched during the scan.

$$y = \hat{m}x + \hat{b}$$

$$\hat{m} = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{n\sum x_i^2 - \left(\sum x_i\right)^2} \quad (1)$$

$$\hat{b} = \bar{y} - \hat{m}\bar{x}$$

In order to increase the speed with which the line following algorithm can be applied, it uses prior knowledge based on the last estimate of the line when it searches for the line in the a new frame. By focusing its search over a narrow window around where the line was last found, the algorithm can quickly determine if the line is still present in the visual image. The assumption being made here is that the image of the line will not move significantly from one frame to the next and that the line itself will not jump suddenly within the image. This assumption is reasonable since the robot does not move very fast and the algorithm operates on the order of 10Hz – fast enough to track changes in the direction or orientation of the line.

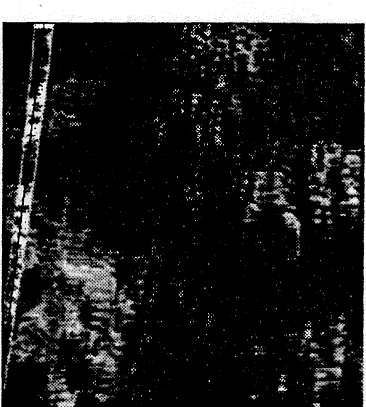

Figure 4 – Tracking the line across the reef. The matched points are superimposed on top of the line with the fitted line display in black.

Once the line has been found in the image, a very simple pursuit algorithm is used to bring the robot onto the heading of the line and maintain its course across the coral. Since the camera is aligned with the axis of travel of the robot, the two frames of reference are aligned. This implies that heading calculations made in the visual frame will map directly to the frame of reference of the robot.

The algorithm determines the intersection of the line with the top of the image and calculates the angle required to bring the intersection of the line to the centre of the image (Figure 5). This is used as the desired heading that is sent to the yaw controller (Equation 2). By keeping the intersection of the line in the centre of the images, the robot's forward motion will tend to bring it onto the line and it will thus be able to follow the line.

$$\psi_d = \arctan\left(\frac{x_i}{h}\right) \quad (2)$$

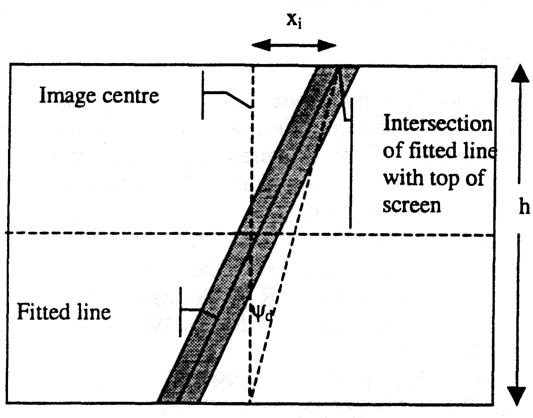

Figure 5 - Visual pursuit of line

Sonar-based Line Tracking

Vehicle localisation is one of the areas of research being worked on in the context of this project. In moving towards the goal of vehicle localisation from natural terrain information, the first step should be the ability to localise based on easily identifiable targets. This allows the localisation problem to be investigated independently of feature extraction, which is a whole research area unto itself.

At present, sonar targets are introduced into the environment in which the sub will operate. These targets present large, easily detectable features for the SeaKing sonar (Figure 7). This sonar will be used to track the position of targets mounted at the ends of the line. By maintaining a fix on two of these targets, the robot can find its current position and orientation relative to the line joining the two targets. Focusing its attention on the targets also allows the robot to more reliably identify the targets in its environment and decreases the region over which the robot must search for the targets during each scan [Leonard and Durrant-Whyte, 1991, 1992].

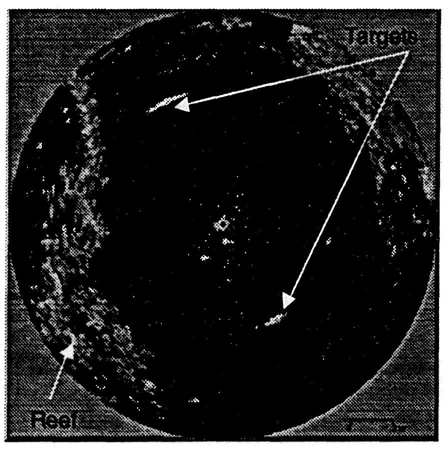

Figure 7 – Sonar scan taken in natural terrain with two targets

Using the range and bearing information to both of the targets, the perpendicular distance from the sub to the line as well as the difference in orientation between the principle axis of the sub and the line are calculated. (Figure 7). These two values can then be used to compute a new desired heading that will bring (or keep) the sub on its desired path. If the sub loses track of the targets, the gyro can be used to maintain control along the line until the targets are reacquired. The two values, ψ and d, represent the observation for a Kalman filter that can be used to track the position of the sub relative to the line.

$$\psi = \arctan\left(\frac{r_2 \sin\theta_2 - r_1 \sin\theta_1}{r_1 \cos\theta_1 - r_2 \cos\theta_2}\right) \quad (3)$$

$$d = r_1 \sin(\psi + \theta_1) \quad (4)$$

$$\psi_d = k_1(d_d - d) + k_2(\psi) \quad (5)$$

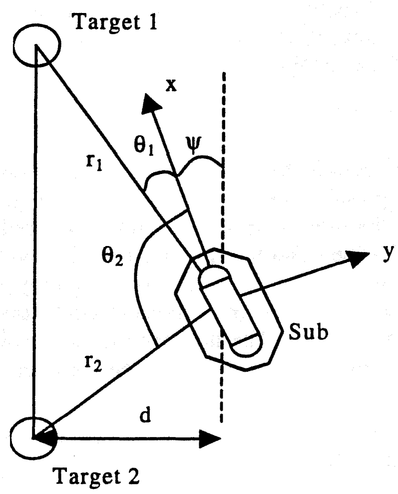

Figure 6 – Sub positioning using fixed targets

The robot computes a desired heading based on the difference in its heading relative to the line and its distance relative to the desired distance to the line. By following a line that is a fixed distance from the targets, multiple targets can be used along the line without the need for the robot to avoid the targets themselves.

The need for multiple targets will depend largely on the terrain and the distance over which the sub must operate. The line tracking ability can be improved with the introduction of more targets along the line. This will also allow the sub to generate a better estimate of its position and orientation because of the redundant information contained in the position of the extra beacons.

Decoupled control

Control of a mobile robot in six dimensional space can be a daunting and computationally intensive endeavour. By decoupling the control problem, individual controller design is greatly simplified. In the case of the Oberon vehicle, vertical motion can be controlled independently of its lateral motion using two separate PID controllers. These controllers can then be tuned to provide the required performance in each case.

The control of the sub is further decoupled into low-level and high-level control processes. The low-level processes run on the embedded controller and are used to interface directly with the hardware. In addition, the PID controllers have been implemented at this level. This allows the PID controllers to respond quickly to changes in the state of the sub without being affected by the data processing and high-level control algorithms running at the surface.

The high-level processes run on a pair of Pentium machines at the control station. Information from the sub's sensors is fed to a series of processes running on these machines. These processes use the data supplied by the sensors to determine the desired set points for the low-level control processes.

These control schemes have proven to be effective in controlling the motion of the sub. It appears that more complicated control schemes relying on complex models of the sub are not necessary in the context of this problem.

This control strategy relies on the ability of the sub to gather information about its environment and reason about its desired actions. By continuously and quickly monitoring the state of the environment, the sub is able to respond to changes as they occur.

Results

We have been testing the Oberon system in a number of locations. At present, we have shown that the strategies adopted are effective in both a swimming pool at the University of Sydney and in a natural terrain environment on Sydney's shore-line. Testing is on-going and the technology is expected to be demonstrated to the AIMS group in the near future. The next step in this project will see the Oberon sub in Cairns for trials on the Great Barrier Reef in Northern Queensland.

Future Directions

This project has enabled the loop to be closed on control of the Oberon submersible vehicle. This represents a major stepping stone in the pursuit of fully autonomous navigation based on natural terrain features.

Certainly one of the most interesting future endeavours that will be pursued by this project will be the adaptation of some of these techniques to a natural environment without relying upon the introduction of artificial sonar targets. Having now closed the loop in a semi-autonomous fashion for controlling the sub, it will be interesting to explore feature-based navigation to accomplish more complex and less structured tasks.

The line following algorithms are currently being studied to increase their reliability under changing lighting conditions and occlusion. The user is still required to provide a hint to initialise the search for the line in the visual frame. Eliminating this requirement will increase the ease with which the algorithm can be used.

As mentioned, obstacle avoidance can be achieved by sharing the Imagenex sonar with the altitude task. This task is under development and will allow the vehicle to make predictions about up-coming changes in the profile of the sea floor. These changes can be used to more reliably predict the desired depth set-point using a scheduling algorithm based on the responsiveness of the sub.

In the more distant future behaviour arbitration, mission planning and navigation using natural terrain features are all areas of on-going research. The subsea environment provides a whole host of interesting opportunities for further study.

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