# A New Robot for Environmental Monitoring on the Great Barrier Reef

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## Abstract

A vast amount of research into autonomous underwater navigation has, and is, being conducted around the world. However, typical research and commercial platforms have limited autonomy and are generally unable to navigate efficiently within coral reef environments without tethers and significant external infrastructure. This paper outlines the development and presents experimental results into the performance evaluation of a new robotic vehicle for underwater monitoring and surveying in highly unstructured environments. The hybrid AUV design developed by the CSIRO robotic reef monitoring team realises a compromise between endurance, manoeuvrability and functionality. The vehicle represents a new era in AUV design specifically focused at providing a truly low-cost research capability that will progress environmental monitoring through unaided navigation, cooperative robotics, sensor network distribution and data harvesting,

## 1 Introduction

The Great Barrier Reef is a dynamic ecosystem and understanding its behaviour, cycles and responses to human interaction is considered essential to ensure that it is effectively managed and remains in its current "pristine" state.

Monitoring and collecting temporal and spatial change information of the reef environment is a vital task and is currently being performed by agencies such as the Great Barrier Reef Marine Park Authority, Australian Institute of Marine Science, James Cook University and CSIRO. However, due to the sheer size of the marine park, approximately 2000 km in length covering 349,000 sq km, only broad-scale, with limited selected fine-scale, monitoring is currently performed, typically by human divers and remote monitoring stations at great operational cost.

In an attempt to improve the monitoring capability of these organisations, new technologies are being developed to increase data collection rates and improve collected data quality and quantity to obtain a more global view instead of inferred views from sparser data streams. However, these technologies are generally remote controlled by human operators or require human operators to deploy. There is currently very little autonomy in the monitoring programs currently in place and this highlights a general need to improve even further the data collection rates and reduced monitoring costs by developing and deploying autonomous robotic systems to assist monitoring authorities in their research.

However, the Great Barrier Reef offers enormous challenges for autonomous robotic systems. The environment is highly unstructured and requires considerable manoeuvring and navigating capability for collecting the correct information. A typical section of the reef in which video survey transects are performed is shown in Figure 1.

Figure 1: Typical highly unstructured terrain the AUV must navigate.

As can be seen from Figure 1, the environment is far from planar, consisting of caverns, overhangs, hard and soft corals, rocks and other obstacles, strong currents, deep and shallow waters, and marine organisms which all make navigation difficult. Many researchers use expensive ROVs and/or acoustic and sonar positioning devices which require considerable infrastructure to be set up to operate effectively. Therefore, this research is considering the fusion and use of vision and inertial sensors to achieve similar performance whilst requiring no external infrastructure to perform the mission at a vehicle cost of the order of magnitude less than current vehicles. There is a small amount of research being performed for navigation in such reef environments [Eustice *et al.*, 2004; Williams and Mahon, 2004], however, although promising research, their methods currently require expensive hardware and offline processing to assist in localisation which is limiting for performing broad-scale surveying tasks.

Development of smaller lower cost Autonomous Underwater Vehicle's (AUVs) has received some attention in recent years with work by WHOI [Prestero, 2001] and Virginia Polytechnic [Stilwell and Wick, 1999] being prime examples. However, these are torpedo style vehicles with limited sensing (no vision) or manoeuvring capability which is considered essential in reef environments. Other larger commercially available AUVs are considered too expensive and the tether and endurance are considered restricting factors.

In light of current technology, there is a need for an autonomous underwater system for performing reliable and efficient in-field environmental monitoring tasks at a much reduced cost then currently available vehicles. This paper describes a system that addresses this need of a low-cost vehicle which uses low-resolution sensors and hardware fused intelligently together to provide reliable localisation estimates and navigation information.

A principle aim of this research was to construct a fully autonomous underwater vehicle for less than AUS$10,000 which requires less than one person/operator per AUV. Additionally this investigation focussed on not only developing an AUV to perform environmental management tasks, but to develop an autonomous systems "capability" which can be scaled appropriately to achieve a variety of unspecified tasks. This capability would allow AUVs to operate in highly unstructured environments with minimal to no human intervention or external positioning infrastructure.

### 1.1 Paper outline

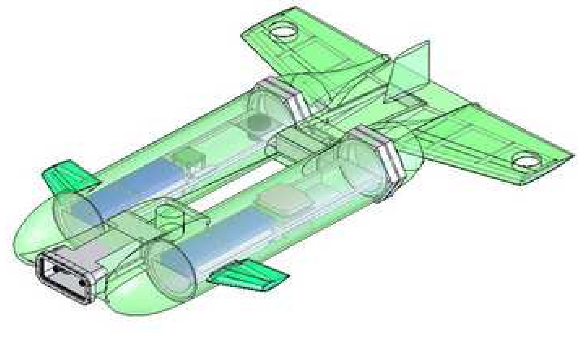
The remainder of this paper is structured as follows. Section 2 provides an overview of the vehicle and the philosphy behind its design, with Sections 3 and 4 outlining the sensors and new technology used on the vehicle. Section 5 describes the vision-based motion estimation technique employed. Finally, Section 6 presents some experimental performance results for the vehicle.

## 2 Vehicle Overview

The autonomous underwater vehicle developed in this research had an overarching goal of being significantly less expensive than other research and commercial platforms (less than AUS$10,000) and that it must be small enough to be deployed from small boats, jetties or from the foreshore. Also it is desired to reduce the ratio of AUVs that can be deployed and operated per person to be greater than one.

The vehicle must be capable of performing the environmental monitoring tasks required by the reef monitoring organisations [English *et al.*, 1994]. The primary tasks to be performed are video transect surveys and water quality measurements. In order to achieve these tasks, the vehicle must be capable of navigating over highly unstructured surfaces at fixed altitudes (down to 300mm from sea floor) at depths in excess of 100m in cross currents of 2 knots. The required positional accuracy in linear transects must be less than 5% of total distance travelled to ensure repeatable transects.

Additionally, in order to effectively navigate around this environment, the physical properties of the AUV must decrease in size and increase in manoeuvrability. Also the size and power requirements of the sensor suite must decrease whilst still providing a speedy and efficient monitoring platform. It is also considered essential that the vehicle be untethered to reduce risk of entanglement, the need for support vessels and reducing drag imposed on the vehicle during strong currents. Figure 2 shows the vehicle design named "Starbug" in its concept form and its current physical configuration.



(a) Concept

(b) Actual

Figure 2: The "Starbug" Autonomous Underwater Vehicle.

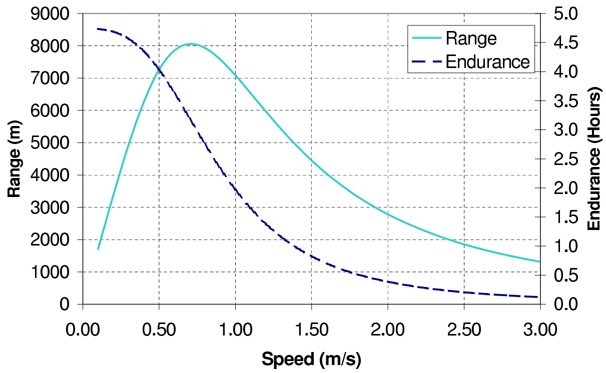



Figure 3: Predicted range and endurance in still water.

The vehicle design is a compromise between endurance, manoeuvrability and functionality. Endurance is best achieved with a streamlined torpedo style vehicle, however, this requires the vehicle to have longitudinal motion to obtain any control authority. Manoeuvrability is best achieved with the well actuated "crate" style vehicles typical of most research platforms. These generally have control authority in multiple directions to allow station keeping although they are power hungry and consequently usually tethered. Both these style of vehicles have limited functionality away from research purposes. The "Starbug" vehicle is a hybrid of these two concepts with extra design features added to increase the functionality of the platform through provisions for manipulators and scientific payloads.

The key performance specifications for Starbug are:

- Mass 26kg
- Length 1.2m (folding to 0.8m for transport)
- Maximum forward thrust 20N
- Maximum speed 1.5m/s
- Speed for maximum range 0.7m/s
- Battery capacity 6.4Ah (4x12V sealed lead acid batteries)

Starbug has been designed with endurance as well as manoeuvrability in mind. Therefore, reducing the drag profile of the vehicle in forward motion has been considered at each stage of the design. Based on the performance theory presented by Signh [Singh *et al.*, 1997], and the measured and inferred physical and electrical specifications of the vehicle an estimation of the vehicle's range and endurance in still water and 80% battery utilisation was made with the results shown in Figure 3.

As seen in Figure 3, the maximum range is approximately 8km at a speed of 0.7m/s with the current batteries and computing hardware. It is anticipated that this range can be extended to approximately 30km by replacing the sealed lead acid batteries with lithium polymer versions with significantly greater capacity.

The vehicle is fully actuated with six thrusters providing forward, lateral and vertical translations as well as yaw, roll and pitch rotations. Although there is capacity for lateral (sideways) motion, this is only marginal compared to the other axes due to the thrusters chosen in this direction. Vehicle control is implemented with each of the motion axis decoupled and the control inputs determined using proportional controllers. This control axis decoupling has proven an effective technique with satisfactory control performance through extensive experimental evaluation.

The thrusters are controlled via a CANBus network which is serially linked to all the thrusters via the single connector. This performs well for this vehicle and has proven reliable in operation. In fact, all internal and external sensors (pressure, IMU and motor drivers) are communicated to and commanded via the CANBus.

## 3 Sensors

The small class of AUV that has been constructed is designed to conduct surveys according to the standards set out by the Australian Institute of Marine Science [English *et al.*, 1994]. The primary tasks that have been identified to be performed autonomously by the vehicle are:

- Video transects
- Water quality monitoring
- Plume monitoring

Due to the desired tasks and the environment in which the vehicle has been designed to operate, vision was chosen as the primary sensor for navigating. Reef environments provide generally clear water with visibility greater than a couple of meters with sufficient lighting (at depths less than 100m) to detect features required for navigation. It is also expected that within coral reef environments there are sufficient features and colour information to allow accurate vision-based odometry estimation.

The sensor platform developed for the Starbug AUV has been based on past experience with the CSIRO autonomous airborne system [Roberts *et al.*, 2002] which has been extended and enhanced to allow a low-cost navigation suite for the task of long-term autonomous broad-scale reef monitoring [Dunbabin *et al.*, 2004].

Vision also allows height and odometry information to be estimated which is required for very close reef navigation. Due to the highly unstructured sea-floor with caverns, steep slopes and drop-offs, more traditional sensors such as sonar could be rendered less effective.

Therefore, the sensor suite and associated hardware chosen for the low-cost navigation platform for Starbug consists of:

- Cameras with video MUX and frame grabber
- IMU
- Magnetic compass
- Pressure sensor (2.5cm resolution)


(a) Inertial plus GPS (b) Stereo camera head

Figure 4: Primary navigation sensors.

- Computer stack
- Low data rate acoustic modem
- GPS

The system consists of two stereo heads with one looking downward to estimate altitude above the sea-floor and odometry, and the other looking forward for obstacle avoidance. The inertial measurement unit was developed by the CSIRO team for the autonomous airborne platform. Its sensors include angular rate gyros, accelerations, magnetometers, absolute attitude and even differential GPS. The cameras used are a colour CMOS sensor from Omnivision with 12mm diameter screw fit lenses which have a nominal focal length of 8mm. Figure 4 shows the inertial and CMOS stereo camera head used in Starbug.

The cameras are set with a baseline of 70mm which allows an effective height resolution in the range 0.2 to 1.7m. The two cameras are tightly synchronized and line multiplexed into PAL format composite video signal. There is also a 3W LED located in the centre of the stereo head to provide a small amount of lighting. The effectiveness of the external lighting system is currently under evaluation.

A PC/104 stack running the Linux operating system provides the software interface to record and process all sensor information in real-time. The final integration of all hardware used for this investigation is packaged into two trays which are placed within each of the two interconnected pressure hull components of the vehicle. The system consists of four batteries, two per tray, with one tray containing the computer stack (CPU, power supply, hard disk) and the video MUX and frame grabber. The other tray contains the IMU and pressure sensor as well as the CANBus hardware. Figure 5 shows the two instrument trays that are contained within Starbug.

## 4 New Technology

The Starbug platform has been designed for reef associated tasks such as water quality monitoring and video transect surveying. Typical current manoeuvring thrusters such as DC motors with shaft propellers have considerable protrusion into the water stream especially

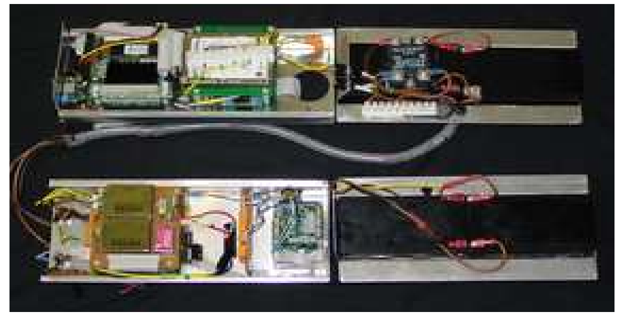


Figure 5: Starbug's sensing and computing instrument trays.

for those actuators which are perpendicular to vehicle motion. This can significantly increase the overall drag of the vehicle. Therefore, in the development of the AUV it was desired to reduce the horizontal drag profile to improve the range and endurance whilst still having sufficient manoeuvrability for station keeping and terrain following.

Therefore, the motivation was to design and build a flat manoeuvring thruster for underwater use which can be integrated into slim control surfaces with low to no additional horizontal drag profile and significant thrust. The resulting design was a novel slim (16mm) thruster in which the entire motor and drive electronics are encapsulated in resin and the propeller is the rotor. Figure 6 shows the first prototype flat thruster developed which fits within the vehicles hydrodynamic surfaces.

Figure 6: Novel low-profile manoeuvring "Flat thruster" designed for high torque and low drag.

The flat thruster is capable of producing in excess of $\pm$10N at efficiencies in excess of 60%. The three phase motor is self contained in that it has its own motor driver, propeller and communication hardware and uses the CANBus communication protocol to drive the motor. This allows any number of motors to be interconnected with only a single hull penetration to the drive computer.

These micro thrusters allow vertical and horizontal motions to be achieved with the vehicle stationary. Additionally, the introduction of these thrusters has reduced the frontal area of each control/stabilization fin by 40%, and the entire vehicle by approximately 14%. This is a considerable saving in drag of the vehicle, directly improving its range performance.

# 5 Vision-based motion estimation

Due to the unique operating environment and the characteristics of the desired tasks for the vehicle such as highly unstructured and feature rich terrain, relatively shallow waters and sufficient natural lighting, vision is considered a viable alternative to typical expensive acoustic positioning and sonar techniques for navigation.

On this vehicle, the downward cameras are used for altitude and translational motion estimation with the front cameras used for obstacle avoidance.

The system uses reasonable quality CMOS cameras with low-quality miniature glass lenses. Therefore, it is important to have an accurate model of the cameras intrinsic parameters as well as the good knowledge of the camera pair extrinsic parameters. Refraction due to the air/water/glass interface also requires consideration as discussed in [Dunbabin *et al.*, 2004]. In this investigation the cameras are calibrated using standard automatic calibration techniques (see e.g. [Bouguet, 2000]) to combine the effects of radial lens distortion and refraction. The use of polynomials to model the combined camera nonlinearities appears sufficient for our preliminary visual odometry studies, however the true accuracy of this assumption requires further investigation.

Additionally, to improve the processing speed of the system, rather than correcting the entire image for lens distortion and refraction effects, the correction is applied to only to the coordinate values of the tracked features, saving considerable computation.

The processing of the captured images consists of five key components in the determination of height and odometry information for the AUV:

- Feature extraction
- Stereo matching
- Motion matching (optic flow)
- 3D reconstruction
- Motion estimation

## 5.1 Features

In this investigation, the Harris feature detector [Charnley *et al.*, 1988] has been implemented due to its speed and satisfactory results. Ultimately, the final solution will consist of a combination of this higher frame rate method with a slower loop running a KLT (or similar) type tracker acting to track features over a longer time period and thus helping to alleviate motion estimate drift.

## 5.2 Stereo Matching

For stereo matching, the correspondences between features in the left and right images are found. Firstly, those corners which cannot be a considered a match due to either a large vertical shift or which would give a negative disparity are disregarded. Then, the similarity between the regions surrounding each corner is computed (left to right). If the match is strong, the corresponding right to left feature check is performed. The similarity is evaluated with a normalised cross correlation similarity measure (ZNCC).

Typically this process involves thousands of evaluations. To reduce computation, epipolar constraints are used to prune the search space and only the strongest corners are evaluated. Once a set of matches is found, the results are then refined with sub-pixel interpolation.

## 5.3 Motion Matching (optic flow)

There is a strong similarity between tracking features over time and over space as in the case of stereo matching discussed in Section 5.2. Given the full set of corners from stereo matching, similar techniques are used to find the corresponding corners from the previous image (currently this matching occurs in either the left or right image as defined at runtime). Image motion is then calculated by subtracting the corresponding pixel coordinates.

Currently, tracking has only a one frame memory. This reduces problems due to appearance change over time, however, as stated earlier, longer term tracking will improve integration drift problems. Future research will look at ways of combining longer term tracking into the current system.

## 5.4 3D reconstruction

Given the stereo matched corners, standard stereo reconstruction methods are then used to estimate a points three-dimensional position. In previous vision-based motion estimation [Roberts *et al.*, 2002], the stereo data was processed to find a consistent plane. The motion data was then processed to find a consistent affine transformation. The underlying assumption for stereo and motion was the existence of a flat ground plane. In this application, it cannot be assumed that the ground is flat as the reef environment does not consist of ground planes. Hence, for height estimation the closest point to vehicle is currently used. Future research will look at the validity of this approach with consideration given to alternate techniques such as dense stereo matching which could be used for height estimation and obstacle avoidance. The primary purpose of reconstruction in this investigation is for visual odometry.

## 5.5 Motion Estimation

Motion estimation is performed in an iterative least squares manner giving a six degree of freedom pose estimate with respect to the previous frame. The first step in this process is to find a set of points which give a three-way match, that is, those points which have both a stereo match in the current frame and a corresponding matching corner from the previous frame. Given this

Figure 7: CSIRO AUV test tank with Starbug.

correspondence, the problem is formulated as one of optimization to find the best vehicle rotation and translation which matches the visual motion and stereo reconstruction.

The resulting pose estimate can then be transformed to a consistent coordinate system using the roll, pitch and yaw data from the IMU. Experimental results of vision-based odometry are given in Section 6.

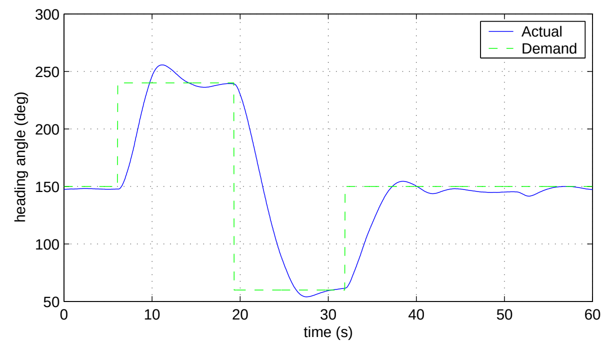
## 6 Experimental Results

An experimental evaluation of the vehicle performance has been conducted without the use of flat thrusters discussed in Section 4. In this investigation, the flat thrusters were not available and therefore smaller lower capacity thrusters (maximum 3N each) for vertical motion have been used.

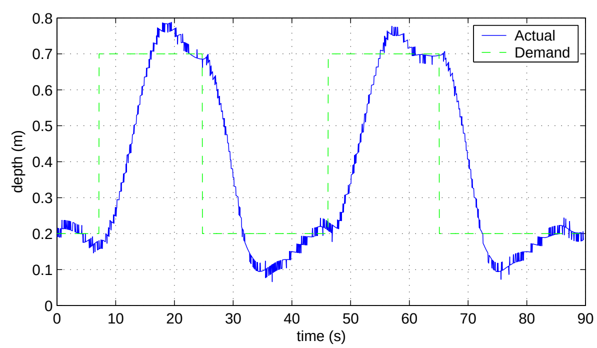
A test tank was constructed at CSIRO's QCAT site. The tank is has a working section of 7.90 x 5.10m with a depth of 1.10m which is sufficient for system and preliminary vision-based control development. The tank is lined with a sand coloured matting with pebbles and rocks covering the floor to provide a texture surface for the vision system which is representative of a reef environment. Figure 7 shows a top view of the vehicle in the test tank.

The manoeuvrability of the vehicle has been evaluated with Figure 8 showing the yaw and depth responses of the vehicle to step command inputs. It can be seen that the vehicle has good response to the inputs with slight overshoot and little steady-state error. The depth response will be considerably improved with the introduction of the flat thrusters.

In order to evaluate the vehicles vision-based odometry system, two rods were attached vertically to the AUV which protrude from the waters surface. A SICK laser range scanner was then used to track these points with respect to a fixed coordinate frame and provide a ground truth for the vision system. Figure 9 shows the results of the vehicle's estimated position using only vision-based motion estimation fused with inertial information during




(a) Yaw




(b) Depth

Figure 8: Yaw and depth tracking response to set inputs.

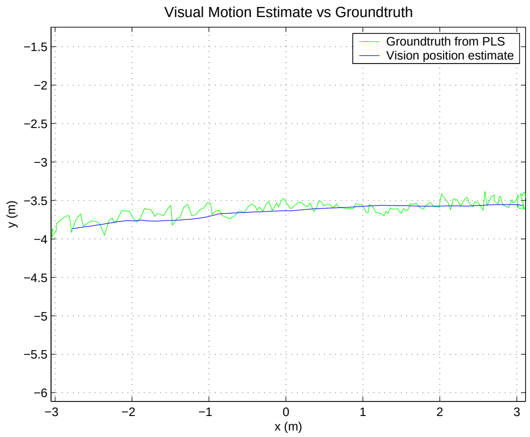



Figure 9: Position estimation using only vision and inertial information in short survey transect. Also shown is a ground truth obtained from the laser system.

a short survey transect. The ground truth obtained by the laser system is shown for comparison.

As seen in Figure 9, the motion estimation compares very well with the ground truth estimation with a maximum error of approximately 2% at the end of the transect. Although, this performance is encouraging, work is being conducted to improve the position estimation over greater transect distances.

## 7 Conclusions

The Starbug AUV project has resulted in the development of a versatile research platform with significant capability and commercial potential. The vehicle has been designed to operate untethered and without external acoustic positioning systems for localisation. Preliminary experimental results show the small AUV is capable of manoeuvring, navigating and operating within highly unstructured reef environments and the low-cost vision and inertial sensor fusion system is capable of performing transect surveying and terrain following tasks. To the best of our knowledge, this is the first vehicle of its type which is specifically designed for performing monitoring and surveying tasks on the Great Barrier Reef.

The current areas of research focus are to integrate vision and GPS (when surfaced) into the navigation and control strategy, underwater sensor network distribution and data harvesting, low-cost sensor development and autonomous docking to a surface vessel.

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