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A Hybrid AUV Design for Shallow Water Reef Navigation

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***Abstract*— The highly unstructured nature of coral reef environments makes them difficult for current robotic vehicles to efficiently navigate. Typical research and commercial platforms have limited autonomy within these environments and generally require tethers and significant external infrastructure. This paper outlines the development of a new robotic vehicle for underwater monitoring and surveying in highly unstructured environments and presents experimental results illustrating the vehicle's performance. 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.**

***Index Terms*— AUV, vision-based navigation, underwater robotics.**

I. 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 numerous agencies. 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, improve collected data quality 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 relatively 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 Fig. 1.

Fig. 1. Typical highly unstructured terrain the AUV must navigate during survey transects.

As can be seen from Fig. 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. There is a small amount of research being performed for navigation in such reef environments [1], [2]. However, although this is promising research, their methods currently require expensive hardware and offline processing to assist in localisation which is limiting for performing real-time broad-scale surveying tasks.

The use of vision in coral reef environments is considered a powerful technique due to the feature rich terrain. Vision hardware is relatively cheaper than other underwater sensors, although, it requires considerably more information processing to obtain necessary data. Therefore, this research considers the fusion and use of vision and inertial sensors to achieve similar performance to acoustic sensor systems, whilst maintaining a vehicle cost of an order of magnitude less than current vehicles.

Development of smaller lower cost AUVs has received some attention in recent years with work by WHOI [3] and Virginia Polytechnic [4] being prime examples. However, these are torpedo style vehicles with limited sensing (no vision) and manoeuvring capability. This makes them unsuitable for reef environments. Other larger commercially available AUVs are considered too expensive and the tether and endurance are considered restricting factors.

Newer novel vehicle designs are exploring alternate power and propulsion systems to increase range and endurance such as the solar powered AUV [5] and the underwater glider technology [6]. These vehicles have been observed to perform well in ocean trials, however, their performance in coral reef environments is still to be evaluated.

In light of current technology, there is a need for an autonomous underwater system for performing reliable and efficient in-field environmental monitoring tasks that cost significantly less 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 to deploy and operate. 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.

A. Paper outline

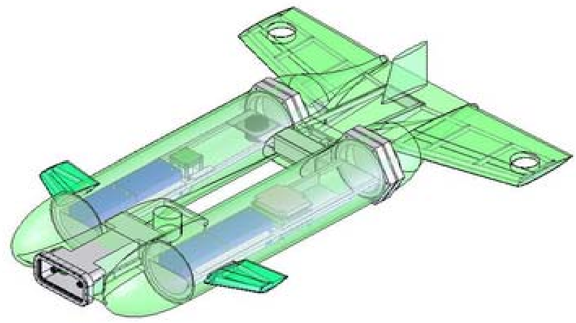
The remainder of this paper is structured as follows. Section II provides an overview of the AUV and the philosophy behind its design. Section III describes the vehicle's sensors and their integration with other hardware and software systems, with Section IV outlining new thruster technology developed for the vehicle. Finally, Section V presents some experimental performance results for the vehicle.

II. 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). It was also required to be small enough to be deployed from small boats, jetties or from the foreshore so to increase the ratio of operated vehicles to human operators to be greater than one.

The vehicle must be capable of autonomously performing the environmental monitoring tasks required by the reef monitoring organisations [7]. 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.

In order to effectively navigate around this environment, the physical properties of the AUV must decrease in size and increase in manoeuvrability. Additionally, 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. Fig. 2 shows the new vehicle design named "Starbug" in its concept form and its current physical configuration.



(a) Concept

(b) Actual

Fig. 2. The "Starbug" Autonomous Underwater Vehicle.

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 deep sea and 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 the Starbug AUV are:

- Mass: 26kg
- Length: 1.2m (folding to 0.8m for transport)
- Pressure hull diameter: 0.15m
- Maximum forward thrust: 20N
- Maximum speed: 1.5m/s
- Speed for maximum range: 0.7m/s
- Hotel load: 1.1 Amps
- 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. Using the performance estimation theory presented by Singh [8], 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 Fig. 3.

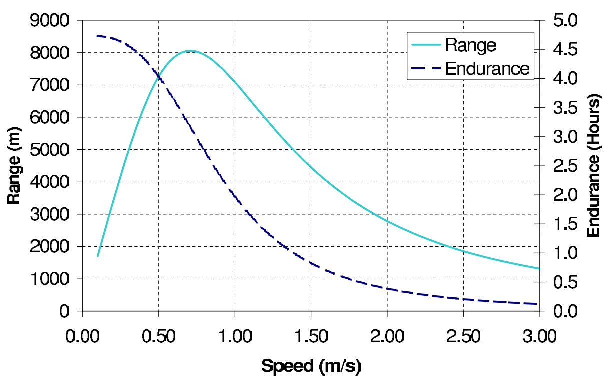


Fig. 3. Predicted range and endurance in still water.

As seen in Fig. 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, vertical and lateral 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 axes 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. Currently, no external moving control surfaces are used in this design. This is to reduce the number of hull penetrations and system reliability.

The thrusters are controlled via a CANBus network which is serially linked to all the thrusters via the single six pin connector. In fact, all internal and external sensors (pressure, IMU and motor drivers) are connected over and communicate via the CANBus. The use of CANBus also reduces the number of hull penetrations and total connector cost and has proven reliable in operation.

III. Sensors

The AUV constructed in this research is designed to conduct shallow water (<100m) surveys according to the standards set out by the Australian Institute of Marine Science [7]. 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 observed from video evidence 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 [9] which has been extended and enhanced to allow a low-cost navigation suite for the task of long-term autonomous broad-scale reef monitoring [10].

Vision also allows height and odometry information to be estimated which is required for very close terrain following and 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
- EiMU (Custom made IMU)
- Magnetic compass
- Pressure sensor (2.5cm resolution)
- Computer stack
- Low data rate acoustic modem
- GPS (when surfaced)

The system consists of two identical 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, accelerometers, 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 6mm. Fig. 4 shows the inertial and CMOS camera sensors used in Starbug.

(a) Inertial plus GPS. (b) CMOS camera.

Fig. 4. Primary navigation sensors.

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 artificial lighting. The effectiveness of the external lighting system is currently under evaluation. Fig. 5 shows the forward looking stereo camera head used on the AUV.

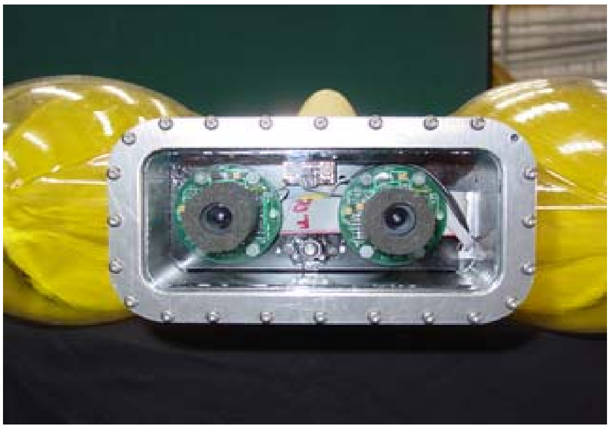


Fig. 5. Stereo camera system.

The sensor suite also consists of a GPS receiver which is only used to obtain a reference position once the vehicle has surfaced. The low-cost acoustic modem provides a low data rate (480bps) communications channel to the vehicle at distances up to 1km. Only vehicle status and high level mission commands are transmitted via the acoustic modem. An operator interface has also been developed which allows a remote operator to specify high-level mission commands via the acoustic modem, as well as hear vehicle status information through audio feedback.

A PC/104 stack running the Linux operating system provides the software interface to record and process all sensor information in real-time. The software system consists of a set of integrated subprograms which implement sensor monitoring, vehicle control, communications, visual motion estimation and vehicle control which are all linked via a custom distributed software architecture [11]. Fig. 6 illustrates the hardware and software integration of the developed navigation system.

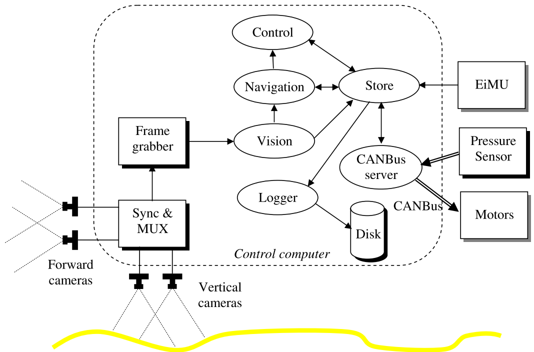


Fig. 6. System hardware and software integration.

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. Fig. 7 shows the two instrument trays that are contained within Starbug.

Fig. 7. Starbug's sensing and computing instrument trays.

IV. New Technology

The Starbug platform has been designed for reef associated tasks such as water quality monitoring and video transect surveying. Typical manoeuvring thrusters such as DC motors with shaft propellers, have considerable protrusion into the water stream, especially 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 little to no additional horizontal drag profile and still providing 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. Fig. 8 shows the first prototype flat thruster developed which fits within the vehicles hydrodynamic surfaces.

Fig. 8. Novel low-profile manoeuvring “Flat thruster” designed for high torque and low drag.

The flat thruster is capable of producing in excess of $\pm$8N at efficiencies greater than 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 control 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 reduction in drag of the vehicle, directly improving its range performance.

V. IN-FIELD RESULTS

An experimental evaluation of the vehicle performance has been conducted without the use of flat thrusters discussed in Section IV. In this investigation, a complete set of 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 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 controller 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. Fig. 9 shows a top view of the vehicle in the test tank.

In order to evaluate the vehicle’s vision-based odometry system, vertical rods were attached to the AUV which protruded from the waters surface. A SICK laser range scanner (PLS) was then used to track these points with respect to a fixed coordinate frame and provide a ground truth for the vision system. Fig. 10 shows the results of the vehicle’s estimated position using only vision-based motion estimation fused with inertial information during a short survey transect. The ground truth obtained by the laser system is shown for comparison.

Fig. 9. CSIRO AUV test tank with Starbug.

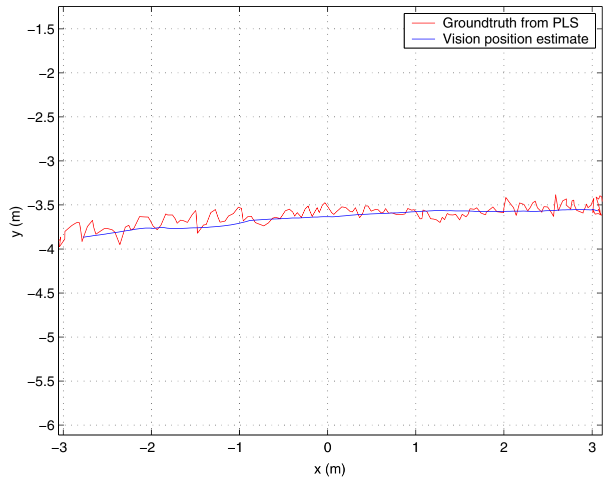


Fig. 10. Position estimation using only vision and inertial information in short survey transect. Also shown is a ground truth obtained from the laser system.

Fig. 10 compares the motion estimation 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. The ground truth system is not considered perfect (as seen by the noisy position trace in Fig. 10) due to resolution of the laser scanner and the size of the rods attached to the vehicle causing slight geometric errors. However, the system provides a reasonably stable position estimate over time for evaluation purposes.

Larger transects using GPS (when surfaced) aided dead-reckoning navigation strategies have been conducted during initial ocean-based field trials. Fig. 11 shows the results of a typical linear transect where the vehicle surfaced every 1 minute to obtain a GPS position correction. The solid line is the vehicle’s estimated position and the circles show the actual location given by GPS. The vehicle maintains good heading control and position estimation over distances representative of video survey transects, however the vehicle drift due to currents is seen by the bias towards the west in actual position provided by the GPS.

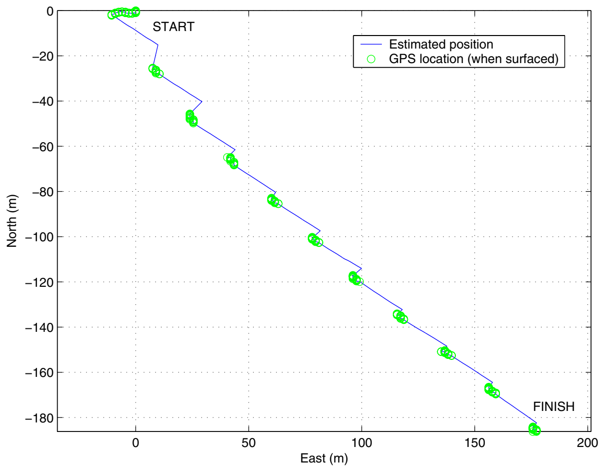


Fig. 11. Position estimation using GPS aided dead-recogning during ocean trials.

The AUV's endurance and long distance vision-based navigation performance is currently being evaluated in ocean trials. Fig. 12 shows the vehicle in a preliminary sea trial for manoeuvrability testing.

Fig. 12. Starbug in ocean trails.

VI. 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 results show that 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 autonomous monitoring and surveying tasks on the Great Barrier Reef.

The vehicle's navigation system consists of low-resolution, low-cost visual and inertial sensors and processing hardware which are intelligently integrated to allow real-time autonomous navigation and vehicle control.

The key areas of research focus for the vehicle are the integration of vision and GPS (when surfaced) into the navigation and control strategy, optimise power management and get the flat thrusters to an operational state. Also a review of the sensor technology and construction methods used on the vehicle is needed to reduce the cost to the desired $10,000. Additional research focus is on the application of this technology in the areas of underwater sensor network distribution and data harvesting, low-cost sensor development and autonomous docking to a surface vehicle.

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