An Autonomous Surface Vehicle for Water Quality Monitoring

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Abstract

This paper describes a novel Autonomous Surface Vehicle capable of navigating throughout complex inland water storages and measuring a range of water quality properties and greenhouse gas emissions. The 16 ft long solar powered catamaran can collect this information throughout the water column whilst the vehicle is moving. A unique feature of this ASV is its integration into a storage scale floating sensor network to allow remote mission uploads, data download and adaptive sampling strategies. This paper provides an overview of the vehicle design and operation including control, laser-based obstacle avoidance, and vision-based inspection capabilities. Experimental results are shown illustrating its ability to continuously collect key water quality parameters and compliment intensive manual monitoring campaigns.

1 Introduction

This work addresses a need to improve the spatial-temporal resolution of data collected on inland water storages and lakes by the development of a unique Autonomous Surface Vehicle (ASV). The system described below is focused on the ability to navigate unsupervised and take precision measurements of water quality and greenhouse gas emissions throughout the water column whilst in motion.

ASVs are rapidly becoming popular globally, particularly within the military, however, they are also becoming commonplace within the marine and aquatic science community. A review of ASV technology by Caccia [Caccia, 2006], describes how ASV prototype systems have been developed for both research and military applications. Typically, the research class of ASVs are lower speed, but more stable catamaran style vehicles, with the military vehicles generally being faster, monohull designs.

The primary areas of research identified in the literature have focused on vehicle design and construction [Curcio *et al.*, 2005a; Larson *et al.*, 2006; Manley *et al.*, 2000; Leonessa *et al.*, 2003; Reed *et al.*, 2006], navigation and control [Vaneck, 1997; Alves *et al.*, 2006; Reyhanoglu and Bommer, 2006] and path-planning and obstacle avoidance [Larson *et al.*, 2006]. The use of multiple ASVs have been proposed to provide communication support for Autonomous Underwater Vehicles [Curcio *et al.*, 2005a; 2005b; Pascoal *et al.*, 2000] and formation control for marine security applications [Bishop, 2004].

An emerging research area is that of mobile adaptive sampling where the ASV can alter its trajectory to improve the measurement resolution in space and time. Zhang [Zhang and Sukhatme, 2007] describe their preliminary work in this area, however, their search space is relatively small where the vehicle movement is faster than the process they are trying to measure. The challenge is now to develop adaptive sampling regimes for significantly large regions where the processes are faster than the vehicles speed.

There are only a few examples of systems designed for long-duration, large-scale unsupervised environmental monitoring. A notable example is by Higinbotham et al [Higinbotham *et al.*, 2008] who have developed solar powered ASV's for ocean and atmospheric observation. Their three vehicle's have conducted long duration missions in open ocean, however, they have no active obstacle avoidance capability. Other examples include a wind and solar powered yacht [Rynne and von Ellenrider, 2008] and an electric catamaran [Wang *et al.*, 2008], however, these are currently in the commissioning phase.

The CSIRO Autonomous Systems Laboratory has for a number of years been developing integrated marine robot and sensor network systems. These systems allow different vehicles to interact at a level to achieve complex tasks such as detect and sample events, inspection, calibration of fixed sensor nodes, and automatic retrieval of Autonomous Underwater Vehicles [Dunbabin *et al.*, 2008]. The work considered here builds on these systems to develop an operational ASV designed for long-duration missions on dynamically changing inland water storages that extend for many hundreds of square kilometres.

1.1 Paper Outline

The remainder of this paper is structured as follows; Section 2 describes the operational requirements and general construction of the ASV. Section 3 provides an overview of the navigation and control strategy employed on the ASV, with Section 4 describing the integration of the ASV with a distributed floating sensor network. Experimental results of the ASV during large-scale sampling missions are shown in Section 5, and finally Section 6 concludes the paper.

2 The Lake Wivenhoe ASV

The pilot deployment site for the ASV was on Lake Wivenhoe. Located west of Brisbane, Queensland (27.3941^{o}S 152.608^{o}E), it has surface area of 109 km^2 with a capacity of 1.16x10^6 ML of drinking water as well as a further 1.45x10^6 ML of flood mitigation for the Lower Brisbane catchment.

The primary role of the robotic boat on Brisbane's water storages is to autonomously navigate and continuously collect water quality information and relay this back to shore in real-time. Operationally and scientifically this has many advantages to current manually intensive; sampling strategies allowing 24 hour sampling, the ability to inspect and capture specific events and locations in a timely manner, and provide a mechanism for quantifying natural variability to drive and calibrate modelling efforts.

A number of design and operational considerations were required in the ASV design:

- Carry a range of specialised (and often large) scientific instruments for water quality and greenhouse gas emission measurement.
- Operate continuously for 24 h from electric sources only.
- Profile the water column whilst in motion.
- Sample at speeds from 0.5 - 3.0 ms^{-1}.
- Operate in wind conditions up to 15 knots.
- Maintain track at speeds as low as 0.5 ms^{-1}.
- Detect a range of obstacles in the water including trees, floating nodes and buoys, boats, and canoes.
- Track and map the shoreline.
- Detect and avoid non-traversable shallow water.
- Operate without line-of-sight communications.
- Station keep for calibration of floating sensor nodes.
- Automatically dock into a cage for safe keeping.
- Be operated manually, remotely and autonomously by non-skilled personnel.

Many of these specifications require compromise between vehicle size, controllability and power. In particular, the range of sensors (navigation and scientific) and general operating conditions (waves and wind) meant that a larger stable catamaran-like vehicle would be the appropriate choice of platforms. Therefore, it was proposed to modify a low-drag 16 ft catamaran with a custom instrument housing which contains solar panels, electric motors, navigation sensors and a profiling arm to allow measurement down to 5.5 m whilst the vehicle is moving. A further design enhancement can allow the sensor payload to be lowered to 20 m when the ASV is stationary.

Figure 1 illustrates the original concept for the ASV. The vehicle has two electric motors to allow heading/tracking control at low speeds and during station keeping.

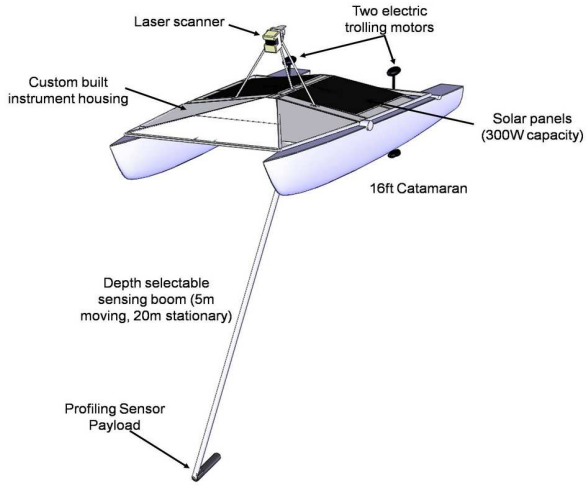


Figure 1: Original concept drawing of the profiling water quality ASV.

Figure 2 shows the actual Lake Wivenhoe ASV during initial commissioning trials.

Figure 2: The solar-powered Lake Wivenhoe ASV.

In order to meet the operational requirements, the ASV is fitted with a suite of navigation sensors which includes a GPS, compass, depth sensor, laser scanner and camera. These all interface with the onboard 1.4 GHz Pentium M processor. The main processor sends serial commands to a dedicated failsafe motor control unit to ensure safe operations of all

mechanically driven devices in the event of communication failure.

Communications on and off-board the ASV are typically via a wireless sensor network interface. The Fleck^{TM} [Corke *et al.*, 2007] sensor network board is the same hardware as in the floating sensor network (see Section 4). Figure 3 shows the general system architecture for the ASV including a typical sensor payload of an Optical Methane Detector (OMD), YSI Sonde (measuring temperature, conductivity, chlorophyll, turbidity, dissolved oxygen, incident radiation), wind sensor and a profiling sonar.

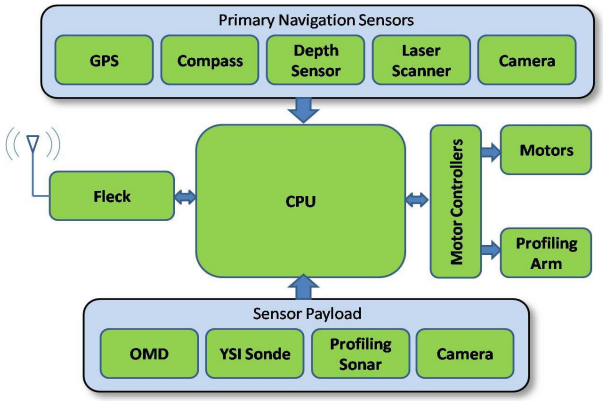


Figure 3: The ASV system architecture.

3 Navigation & Control

At the highest level, missions are specified as a series of waypoints with functionality tags (such as profile, station keep, dock) and the vehicle attempts to maintain a straight path between waypoints. As obstacles are detected using the laser scanner or cameras, their position is projected into a global coordinate system and a prespecified exclusion zone set around the object. If the vehicle anticipates it will breach the exclusion zone, it modifies its path (generally towards the deep water channel) until clear of the obstacle and then resume tracking the desired path.

A series of experiments were conducted to identify and determine key hydrodynamic and propulsive parameters for modelling and control of the ASV. It was determined that with the standard propellers the maximum vehicle speed is 5.5 kts, however, for a continuous solar input of 300 W the sustained speed should be less than 4 kts to not draw from batteries.

A particular challenge with this ASV is controllability at low speed to maintain a desired trajectory as the control effectiveness of rudders increases with the square of velocity. At relatively low survey speeds (less than 1.0 ms^{-1}) as typical of many profiling sensor missions, this means that the vehicle must use a combination of control inputs such as differential thrust from the two electric motors (F_L , F_R) as well as rudder deflection (δ) to maintain track.

Figure 4: The ASV is integrated with an array of 50 floating sensor network nodes (orange buoy behind the ASV) for communication and event detection.

A number of different control strategies were implemented with the most effective being a modified version of the potential field approach of [Dunbabin *et al.*, 2008]. Key modifications include velocity dependant obstacle fields, the provision of moving obstacles and targets, preference for deeper water channels and avoidance of regions of non-traversable shallow water. The tracking performance can be easily specified with a single “track alignment gain”. This alignment gain directly affects control power and endurance particularly at low survey speeds and high wind. A paper describing the details of the low-level controllers and integration with the mission and obstacle trajectory planners is currently under development.

4 Sensor network integration

A key feature of many of the robotic systems developed at CSIRO is their ability to interface directly with static and mobile sensor network systems [Dunbabin *et al.*, 2006; 2008].

A 50 node floating sensor network based on the Fleck^{TM} wireless sensor network devices has been deployed on Lake Wivenhoe [Dunbabin *et al.*, 2009]. These relatively low-cost nodes are distributed across the storage measuring temperature throughout the water column. The continuous monitoring of these nodes enables early detection of events, such as algal blooms, and validation of modelling and prediction against the incoming data. The network also provides backchannels to communicate with, and interrogate, any node or robotic system within the sensor field.

The ASV uses the sensor network for non-line-of-sight two way communications with remote operators. Remote Procedural Calls (RPCs) are used to action the ASV to perform particular tasks. Typical tasks relate to internode sampling, analysing of detected events, as well as in-situ calibration of the floating sensor nodes. Figure 4 shows the ASV with one of the Lake Wivenhoe sensor nodes in the background.

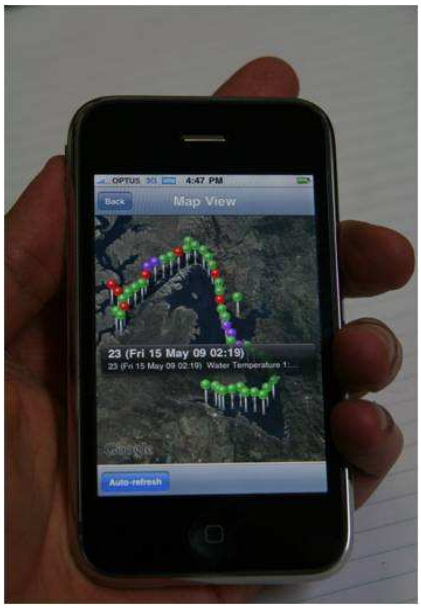


Figure 5: The operators remote field interface. The colors indicate the status of static and mobile sensor nodes and real-time information can be displayed. ASV missions can be generated and uploaded via the interactive interface.

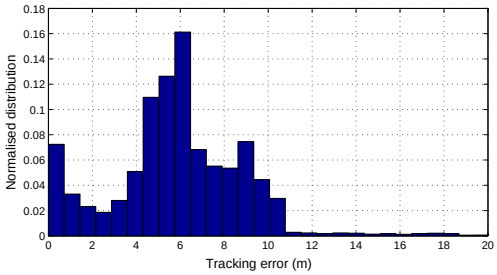
A suite of tools have been developed to allow operators (both in and out of the field) and modelling staff to action the ASV, access current and historical data via the sensor network, as well as remotely control the ASV or plan and upload new missions. Figure 5 shows the web-enabled mobile phone field supervisor's interface.

5 Experimental Results

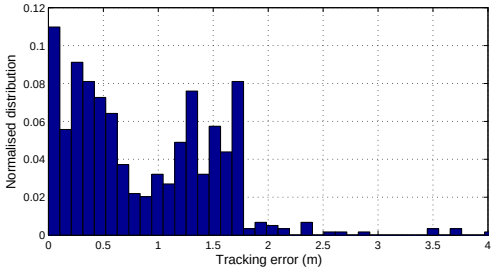
The ASV has undergone extensive field trials to evaluate the performance in a variety of weather conditions and operational scenarios. Key assessment areas include tracking performance (with and without profiling arm deployed), obstacle avoidance and inspection tasks.

The long-term tracking performance of the ASV with different track alignment gains (see Section 3) and wind disturbances is illustrated in Figure 6. In this figure, the ASV's speed was commanded to 1.0 ms^{-1}. It can be seen that at the relatively low-power "standard" alignment gain the tracking error is within 10 m even under wind conditions of 15-20 kts. The tracking error is reduced to 2 m with a higher "precision" track alignment gain.

Using the laser-based obstacle detection strategy described in Section 3, the ASV is capable of detecting the presence and location of a range of static obstacles which include floating sensors nodes and pontoons. This detection and avoidance of static or slow moving (less than 0.5 ms^{-1}) obstacles has been demonstrated up to a nominal maximum speed of 3 ms^{-1}. The detection and avoidance of fast moving vessels is a current area of research.



(a) Standard precision tracking gain (27 km total distance)



(b) High precision tracking gain (2 km total distance)

Figure 6: Normalised tracking error distribution for combined missions and variable wind speeds up to 20 kts.

Figure 7 shows an example of a measured obstacle avoidance manoeuvre trajectory with the ASV travelling at 0.9 ms^{-1}. The obstacle, a floating sensor node, was detected using the laser scanner and the required safety exclusion zone was set at a radius of 15 m. As can be seen, the ASV was capable of localising the obstacle and modifying its trajectory to maintain the safe distance from the obstacle and then realign with the desired path.

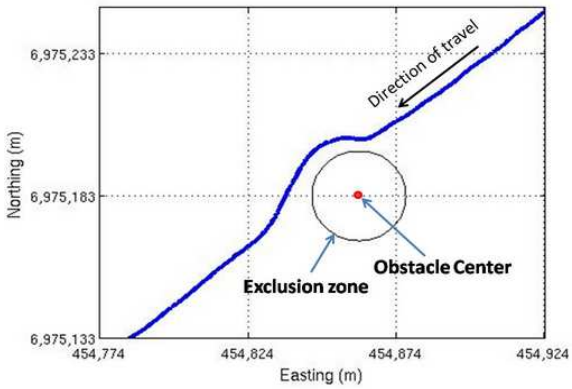


Figure 7: Example of measured ASV trajectory after detection of an obstacle whilst travelling at 0.9 m/s. The obstacle detection range was 30 m.

An experimental investigation was conducted to assess the viability of using vision to detect objects of interest, such as floating nodes to improve longer range obstacle detection.

Figure 8 shows the results of image segmentation to extract the target (a floating sensor node) from a camera mounted on the ASV using background subtraction with color and model-based classification.

Figure 8: Image segmentation of a target of interest (floating sensor node) to allow longer and shorter range tracking for obstacle avoidance and station keeping.

Finally the long term performance of the entire system has been evaluated by conducting repeat sampling missions using the profiling sensor arm. Figure 9 shows the actual trajectory of a 13 km mission conducted on Lake Wivenhoe. The measured water depth is capable of highlighting recently submerged vegetation (between C and D) characterised by the shallower noisy water depth measurement. The temperature trace, shown here for 1.5 m below the surface, shows a general increase in water temperature as the ASV moves towards the base of the storage which appears to be independant of time of day. The hypothesis surrounding this increase in temperature is currently being assessed by water storage modellers.

6 Conclusions

A novel Autonomous Surface Vehicle (ASV) capable of navigating throughout complex inland water storages has been presented. The custom built solar powered catamaran is capable of collecting various water quality information throughout the water column whilst in motion, as well as measuring the spatial-temporal release of various greenhouse gas emissions. The integration of onboard sensors including a GPS, laser scanners, sonars and cameras allow the ASV to operate successfully in previously unmapped shallow water environments, as well as avoid static and mobile obstacles. The ASV is directly integrated with a storage-scale fixed and mobile sensor network to allow high-level operations such as non-line-of-sight communications, mission uploads, data-upload, in-situ inspection and calibration of sensors. Extensive field trials have demonstrated the ability of the ASV to continuously sample the water column and operate in a variety of weather conditions and at night. The operation and data collected by the ASV is complimenting existing manual monitoring campaigns with improved spatial and temporal monitoring of the water storage with hundreds of kilometres of survey already completed.

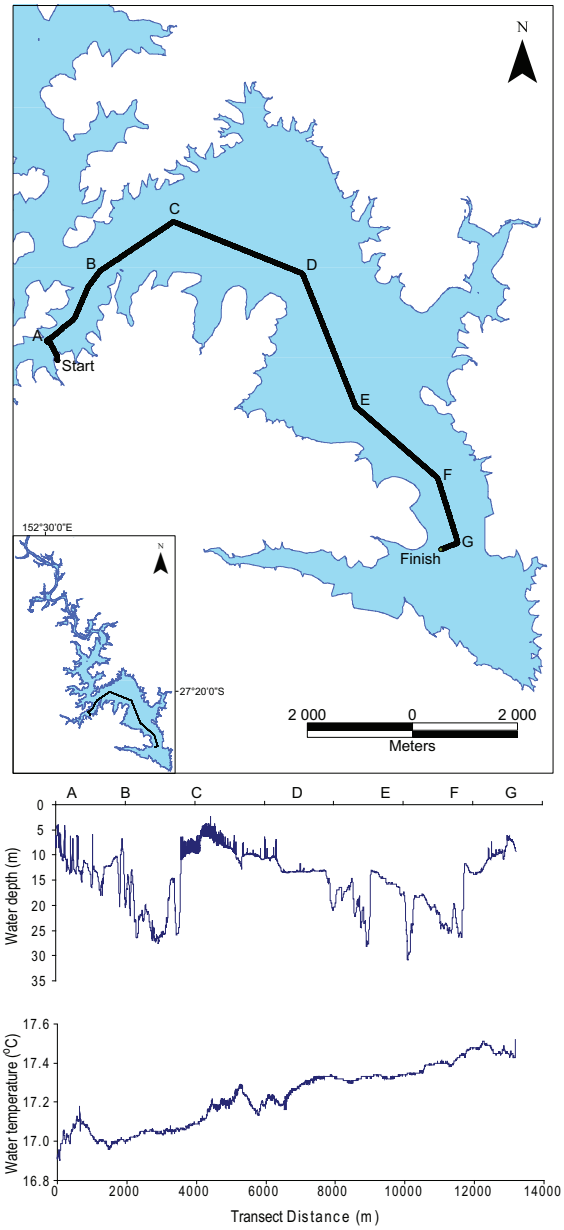


Figure 9: Measured trajectory taken by the ASV during a 13 km sampling mission showing traces of the measure water depth and temperature taken at 1.5 m below the surface.

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