7

The State-of-Art of Underwater Vehicles – Theories and Applications

W.H. Wang[1], R.C. Engelaar[2], X.Q. Chen[1] & J.G. Chase[1]
[1] *University of Canterbury, New Zealand*
[2] *University of Technology, Eindhoven, Netherlands*

1. Introduction

An autonomous underwater vehicle (AUV) is an underwater system that contains its own power and is controlled by an onboard computer. Although many names are given to these vehicles, such as remotely operated vehicles (ROVs), unmanned underwater vehicles (UUVs), submersible devices, or remote controlled submarines, to name just a few, the fundamental task for these devices is fairly well defined: The vehicle is able to follow a predefined trajectory.

AUVs offer many advantages for performing difficult tasks submerged in water. The main advantage of an AUV is that is does not need a human operator. Therefore it is less expensive than a human operated vehicle and is capable of doing operations that are too dangerous for a person. They operate in conditions and perform task that humans are not able to do efficiently, or at all (Smallwood & Whitcomb, 2004; Horgan & Toal, 2006; Caccia, 2006).

First developed in the 1960's, development was driven by the demand from the US Navy (Wernli, 2001), which required them to perform deep sea rescue and salvage operations. In the 1970s, universities, institutes and governmental organizations started with the experimentation with AUV technology. Some of them were successful, most were not. Despite this, there was significant advancement in the development of AUVs. Since then, other sectors have realized the potential of such devices for all manner of tasks. The first of these was the oil and gas industry. These companies employed AUVs to reinforce in the development of off shore oil fields (Williams, 2004). In the 1980's, AUVs came into a new era as they were able to operate at depths well below commercial diver limits. Falling oil prices and a global recession resulted in a stagnant period in terms of AUV development in the mid 1980s. During the 1990s there was a renewed interest in AUVs in academic research. Many universities developed AUVs. This research was followed by the first commercial AUVs in 2000 (van Alt, 2000; Blidberg, 2001). Since then, AUVs have been developing at a fast rate (Smallwood et al., 1999; Griffiths & Edwards, 2003).

AUVs are now being used in a wide range of applications, such as locating historic ship wrecks like the Titanic (Ballard, 1987), mapping the sea floor (Tivey et al., 1998). More mundane applications consist of object detection (Kondoa & Ura, 2004), securing harbours, searching for seamines (Willcox et al., 2004), and, most recently, in scientific applications

(Curtin & Bellingham, 2001; Rife & Rock, 2002; Lygouras et al., 1998). In the past few years, advances in battery design and manufacture have led to batteries with high power densities, which have significantly increased the endurance of AUVs (Wilson & Bales, 2006). At the same time, the development of new technologies made the AUVs more accurate.

This book chapter aims to highlight theories and applications of technologies that are suitable for AUVs by literature review and a detailed AUV design. The chapter is therefore organized as follows. Firstly, Sections 2-6 provide an overview of the latest developments of five different subjects of an AUV, including: 1) the structure of AUVs; 2) controls and navigation; 3) propulsion, drive and buoyancy; 4) sensors and instrumentation of AUVs; and 5) power supply of AUVs. Next, Section 7 reports a relatively low-cost AUV recently developed at the University of Canterbury for shallow waters. Finally, future work and conclusions are given in Section 8.

2. Structure of AUVs

One of the most important aspects of an AUV is the hull. There are a number of different ways in which hull design can be approached (Allmendinger, 1990). These different design methods are typically specific to the situation/task. The main hull must be able to meet a number of key challenges.

Aspects that must be considered during hull design include:

- Pressure and/or depth required
- Operating temperature ranges
- Structural integrity for additions and tapings
- Impact conditions
- Water permeability
- Visual appeal and aesthetics
- Accessibility
- Versatility
- Practicality
- Restrictions for future additions
- Size requirements
- Corrosion and chemical resistance

Among these considerations, the hull of the AUV must be able to withstand the hydrostatic pressure at the target depth. Furthermore, it is desired that the hull is designed in such a way that the drag is minimized. When the vehicle moves at a constant speed, the thrust force is equal to the drag force. The less drag the AUV experiences, the less propulsive power is needed. These two requirements, the ability to withstand the hydrostatic pressure and the minimization of the drag, are dependent of the shape and size of the vehicle. The hydrostatic pressure is given by Equation (1).

$$P = P_a + \rho g h \tag{1}$$

With P the hydrostatic pressure in N/m^2, P_a the atmospheric pressure at sealevel in N/m^2, ρ the density of the water in kg/m^3, g the gravitational acceleration in m/s^2 and h the depth in m. The hydrostatic pressure increases with approximately $10^5 N/m^2$ per 10 meters. The hull must be able to withstand this force. A sphere is probably the first shape that comes into ones head, it is a good shape for withstanding pressure, but not for stability (Paster, 1986). A circular cylindrical hull is a good shape to resist the pressure (Ross, 2006). Many of the current AUVs have a circular cylindrical hull including the most popular in military and scientific use, the REMUS100 (Hsu et al., 2005; Evans & Meyer, 2004; Maurya et al., 2007). Some examples are shown in Figures 1. to 3.

Fig. 1. The HUGIN 4500 autonomous underwater vehicle during deployment for sea trials (Kauske et al., 2007)

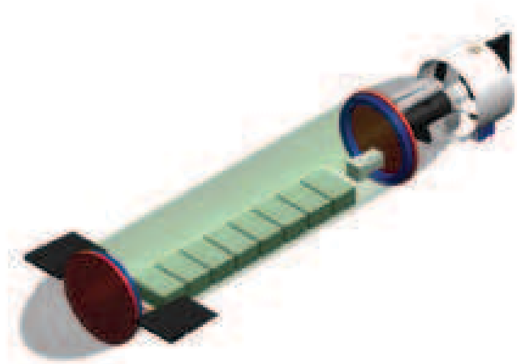


Fig. 2. The Cal Poly AUV model (Monteen et al., 2000)

Fig. 3. The Seahorse AUV (Tangirala & Dzielski, 2007)

Some of the advantages of a cylindrical hull are (Ross, 2006):

- It is a good structure to resist the effects of hydrostatic pressure;
- Extra space inside the hull can be achieved by making the cylinder longer;
- It is a better hydrodynamic form than a spherical form of the same volume; and
- It can be easily docked.

The disadvantages of a cylindrical hull are the cavitation (Paster, 1986), and the instability of the vehicle (Ross, 2006). Cavitation is a phenomenon caused by the pressure distribution generated by the moving vehicle. The difference in local velocity of the body surface results in a pressure distribution. The point that has the maximum rate of change in curvature of the body has the negative minimum pressure. If this pressure reaches the vapor pressure of water, the water will start to boil. The bubbles formed by this boiling collapse when they reach the point where the pressure increases again. The collapse of the bubbles generates very high pressure. This leads to high noise levels and the possibility of damaging the vehicle (Paster, 1986).

Every object that moves in the water experiences drag force. This drag force (in Newton) is given by Equation (2).

$$F_{drag} = 1/2 \cdot \rho \cdot v^2 \cdot c_d \cdot S \tag{2}$$

With ρ the density of water $[kg/m^3]$, v the velocity of the vehicle in m/s, c_d the unitless drag coefficient of the vehicle and S the surface area of the vehicle normal to the moving direction in m^2. The drag coefficient is dependent on the shape of the underwater vehicle. The nose of the circular cylinder used to be spherical, but this caused instability and cavitation (Paster, 1986). The shape of the nose was finetuned to resemble the front of a teardrop (Paster, 1986). A good hydrodynamic body shape design will reduce the drag and improves the range of the vehicle by 2 to 10 times, according to (Paster, 1986).

Another choice that needs to be made in the design phase, is the choice for the material of the hull. The material should have a good resistance to corrosion, have a high strength to weight ratio and must be affordable. In the past, the most used material was steel. In (Ross, 2006) four materials are compared; high strength steel, aluminium, titanium and composites. The advantages of high strength steel are the price and the fact that it is commonly used, so there is much knowledge of it. The major disadvantage of steel is the low strength to weight ratio.

Aluminium has a better strength to weight ratio than steel and is widely available. The drawback of aluminium is that it is anodic to most other structural alloys, making it vulnerable to corrosion. The strength to weight ratio of titanium is even better than that of aluminium, but it is an expensive material.

The most commonly used composite for marine vehicles is glass-fiber reinforced plastic (GFRP). GFRP is cheap with respect to other composites and has a very high strength to weight ratio. Carbon fiber reinforce composites (CFRP) are about 3 times more expensive than GFRP, but have a much higher tensile modulus than GFRP. Metal matrix composites (MMC) have a lot of advantages over GFRP and CFRP but are still in the development phase, making them very expensive (about 15 times more expensive than GFRP).

Another material that can be used for AUVs is acrylic plastic. Acrylic is already the most used material for pressure resistant viewports (Stachiw, 2004). The main advantages of acrylic are that it does not corrode and has a good strength to weight ratio. Furthermore, acrylic is transparent and there are acrylic submersibles that operate at depths up to 1000 meters below the surface.

AUVs that have an operating depth of tens of meters can also be constructed of PVC. The material is widely available and very cheap. With a hull made of PVC it is also easy to mount components on it (Monteen et al., 2000). Table 1 summarizes the properties of each material discussed. The specific strength is given by the ratio of the yield strength and the density.

Material	Density (kg/dm^3)	Yield strength (MPa)	Tensile modulus (GPa)	Specific strength (kNm/kg)
High strength Steel (HY80)	7.86	550	207	70
Aluminium alloy (7075-6)	2.9	503	70	173
Titanium alloy (6-4 STOA)	4.5	830	120	184
GFRP (Epoxy/S-lass)	2.1	1200	65	571
CFRP (Epoxy/HS)	1.7	1200	210	706
MMC (6061 Al/SiC)	2.7	3000	140	1111
Acrylic	1.2	103	3.1	86
PVC	1.4	48	35	34

Table 1. Material properties, from (Ross, 2006) and (Stachiw, 2004)

According to numerous authors the cylindrical shape is a very good one for an AUV. In the future MMC may be the best choice for the material, but until then GFRP is a good choice for AUVs. If the operating depth is only tens of meters, PVC is a good and cheap alternative.

3. Controls and navigation

An AUV must be able to operate autonomously. In order to achieve this it is essential that the computer in the AUV knows its current location at all time. This can be done by means of an accurate navigation system. Another reason that the AUV has got to know its location is because of the fact that gathered data is pretty much useless if the location from which it has been acquired is unknown (Leonard et al., 1998). To navigate properly a good, accurate controller is necessary for which first a mathematical model of the AUV is needed. The basic model for the AUV is described in Equation (3).

$$\begin{aligned} \mathbf{M}\dot{\nu} + \mathbf{C}(\nu)\nu + \mathbf{D}(\nu)\nu + \mathbf{g}(\eta) &= \tau \\ \dot{\eta} &= \mathbf{J}(\eta)\nu \end{aligned} \tag{3}$$

Where **M** is the inertia matrices for rigid body and added mass, $\eta = [x, y, z, \phi, \theta, \psi]^T$ the position and orientation (Euler angles) in inertial frame, $\nu = [u, v, w, p, q, r]^T$ the linear and angular velocities in body-fixed frame, **C** is the Coriolis matrix for rigid body and added mass, **D** is the quadratic and linear drag matrix, **g** is the buoyancy and gravity forces, τ is the thruster input vector and **J** is the coordinate matrix which brings the inertial frame into alignment with the body-fixed frame. The model is described in detail in (Fossen, 1994).

When a model is made for the vehicle it is possible to design a controller. For low speed vehicles, the horizontal and vertical movements can be decoupled, which makes the model of the vehicle less complex (Maurya et al., 2007; Williams et al., 2006; Ridao et al., 2001). Because a single fixed linear controller is not sufficient to deal with all the vehicle dynamics, a gain-scheduled controller is often used (Kaminer et al., 1995). First, a number of controllers are designed for a finite number of linearized models using H_∞-control. H_∞-control rests on a good theoretical basis and offers clear guidelines to achieve robust performance in the case of uncertainties in the plant (Zeng & Allen, 2004; Fryxell et al., 1996). These controllers are then combined using gain-schedule on some variables, making the overall controller a linear time-varying system. In multiple articles (e.g. Zeng & Allen, 2004; Jalving, 1994) three different controllers are designed. One is used to control the speed, the other for the heading and the last one for the depth.

In (Valavanis et al., 1997) four different architectures for control are described. The hierarchical architecture is a top-down approach which uses levels. The higher levels are responsible for overall mission goals, while the lower levels solve particular problems. It has a serial structure, which means that the higher levels send commands to lower levels. It is a well-defined structure, but has a lack of flexibility. The heterarchical architecture is a parallel structure. It has flexibility and is suitable for parallel processing. However, due to lack of supervision the communication can be intensive. With the subsumption architecture the different behaviors work in parallel, however one layer can subsume another layer. This architecture is robust and exhibits true dynamic reactive behavior. The disadvantage is the difficulty to synchronize the system.

Finally, the hybrid architecture is a combination of the three architectures. It is divided into two levels. The higher level uses hierarchical architecture while the lower uses either heterarchical or subsumption to control the hardware. It combines the advantages of the three architectures and is used in many vehicles (Williams et al., 2006; Valavanis et al., 2997; Gaccia & Veruggio, 2000). (Gaccia & Veruggio, 2000) makes use of an inner and an outer control loop. The inner loop is used for the control of the velocity and the outer loop is used for guidance control and to set the reference velocities.

When a controller is designed for the vehicle, the navigation system can be implemented. According to (Stutters et al., 2008) the accuracy of position estimation will degrade over time if the position of the AUV is not externally referenced. The lack of easy observable external references makes AUV navigation very difficult.

Leonard et al. (1998) describes the three primary methods of navigation, dead-reckoning and inertial navigation systems, acoustic navigation and geophysical navigation techniques. The sensors and instrumentation used for the measurement of the different variables are described in Section 5. Dead-reckoning integrates the vehicle velocity in time to obtain the position. The information is then processed by a Kalman filter which gives an estimate of the current position. The velocity measurement can be affected by sea currents, so operations near the seabed use Doppler velocity logs (DVL, see Section 5) to measure the velocity with respect to the ground. Inertial navigation uses the acceleration of the vehicle and integrates this twice. This is more accurate then the velocity measurement, but the initialization can be difficult (Lee et al., 2007).

The problem with both systems is that the position error increases as the distance traveled increases. This can be solved by surfacing the vehicle from time to time to obtain the correct position via GPS, but this is not always an option. There are some vehicles, using DVL, that are accurate to 0.01% of the distance traveled (Leonard et al., 1998).

A typical block diagram of an inertial navigation system is shown in Figure 4. Acoustic navigations use external transducers which return the acoustic signal send out by the vehicle. The travel time of the signal determines the position of the vehicle. However, reflections and differences in signal speed can negatively influence the measurement. Geophysical navigation uses a priori knowledge of terrain to identify the current position.

The disadvantage of this system is that the maps of the terrain must exist, and this is not always the case. It also requires a lot of computational power to find the current position. To minimize this, the sys tem can be used in combination with dead-reckoning to limit the search area. The reliability of the system depends on the accuracy of the a priori map. With concurrent mapping and localization the vehicle builds up a map of its environment and uses that map to navigate in real time.

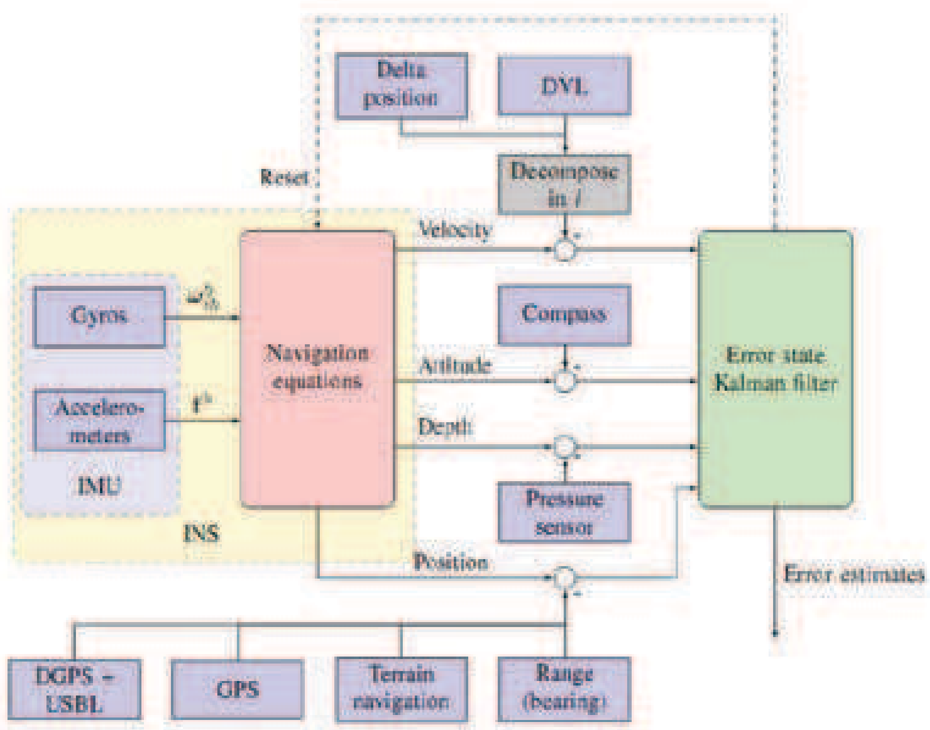


Fig. 4. Aided inertial navigation system (Fauske et al., 2007)

For short-range missions, up to 10km, calibrated inertial navigations systems can provide sufficient accuracy. The system can be extended with a DVL. For longer missions, up to 100km, the path taken by the AUV has a large effect on the accuracy. Concurrent mapping and localization works well for these missions, as long as the path contains many crossover points the technique corrects inaccuracies. Above 100km a geophysical navigation system is the only suitable solution. However, this technique is limited by the availability of maps (Stutters et al., 2008).

4. Propulsion, dive and buoyancy

The most common form of propulsion is via thrusters. For vertical movement thrusters or variable buoyancy systems can be used. The thrusters provide more accuracy and a faster response. If it is not a problem that the vehicle has to move horizontally in order to move vertically the vehicle can also use a single thruster for both the horizontal and vertical movement with the use of diving planes or a robotic wrist.
The kind of propulsion, the drive and the choice for the buoyancy are of great influence on the dynamics of the vehicle. There are a lot of choices that have to be made in the design

phase. The horizontal movement of an AUV is usually empowered by thrusters. One of the reasons for this is that most underwater vehicles are powered by batteries (Smith et al., 1996) (see Section 6 for more information). In (Valavanis et al., 1997), 25 AUVs are described, of which the majority use thrusters for propulsion. The vertical movement can be done with thrusters or by a variable buoyancy system. The buoyancy of an AUV is the upward force on the vehicle that is caused by the surrounding water. If the buoyancy force is equal to the gravitational force on the vehicle, the vehicle is said to be neutral buoyant. It will neither sink nor rise.

When thrusters are used, the vehicle has neutral buoyancy (Serrani & Conte, 1999). The vehicle is then able to move vertically by using the thrusters. One of the advantages of this method is that the vehicle is able to hover without propulsion. A disadvantage of the technique is that the thrusters must remain on will moving vertically, thus consuming power.

There are four static and dynamic diving principles (Wolf, 2003): i) a piston type ballast tank; ii) a hydraulic pump based ballast system; iii) an air compressor based system; and iv) direct thrust systems. The first three concepts come from static diving technology, while the last concept is a dynamic diving technology.

The piston ballast tank (Figure 5a) is one of the most common static diving methods applied in submarine modeling. A piston ballast tank consists of a cylinder and a movable piston, and it works as a large syringe pump. With one end of the cylinder connected to surrounding water, movement of the piston sucks water in or pushes it out. When water fills the tank, negative buoyancy is achieved, so the AUV starts to descend. Conversely, when the tank is emptied, the AUV is positively buoyant, so it ascends. This setup also allows control of pitch motions of the AUV. Moreover, the pistons can be moved by a linear actuator, which is electrically easy to control. Hence, accurate depth control can be achieved with proper, yet straightforward, programming.

A hydraulic pumping system (Figure 5b) is similar to the piston ballast tank, but uses an internal reservoir of hydraulic fluid and a pump to actuate the piston's linear motion. Control of the valves and the pump for the hydraulic fluid allows it to flow in and out of the cylinders, so the surrounding water can be pumped in and out. Consequently, buoyancy of the AUV is changed.

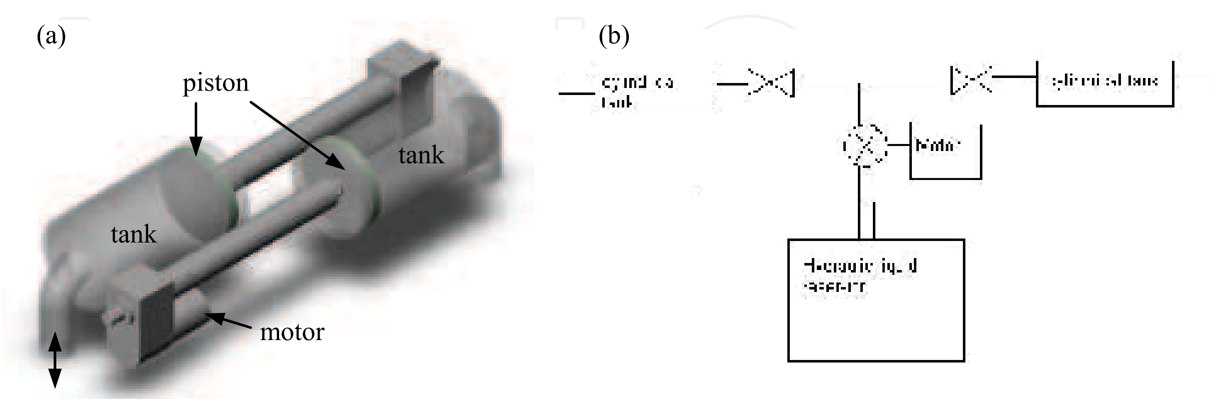


Fig. 5. Examples of two diving principles. (a) Piston ballast system with two tanks. (b) Schematic sketch of hydraulic pumping system

Air compressor systems are commonly used in some classes of submarine. The system is composed of a storage tank of compressed air, a water tank and two valves that are normally closed. To descend, the vent valve is opened, so the pressure difference results in water flowing in from the opening in the bottom of the water tank. When a desired amount of water is obtained for ballast, the vent valve is closed. In order to force the water out, the blow valve is opened to allow the compressed air into the tank so that water is pushed out via the bottom opening. Thus, by letting the water in and out of the water tank, the buoyancy of the AUV is changed.

Thrusters are a dynamic diving method. They require the AUV to be near neutrally buoyant. This approach uses the vertically mounted thrusters to force the AUV to dive. Turning off the thrusters or using them at a thrust less than the positive buoyancy allows controlled ascent. However, this method consumes a lot of power to keep the AUV under water, as the thrusters must remain powered at virtually all times. Being positively buoyant, however, this method is intrinsically failsafe, as the vehicle will come to the surface in the event of a power failure.

With a variable buoyancy system the vehicle is able to vary its buoyancy. The system usually contains a number of tanks that can be filled with water or gas. With this system the vehicle is able to move vertically by changing its buoyancy. Vertical movement and hovering is then possible without propulsion. The drawback of the system is that it is not as accurate as using thrusters. In (Tangirala & Dzielski, 2007) a variable buoyancy system is described that consists of two water tanks with pumps and valves. If more negative buoyancy is needed, the tanks are open to seawater. If positive buoyancy is needed, the water is pumped out of the tanks. In (Wasserman, 2003) a vehicle is proposed that uses air to acquire more positive buoyancy. The vehicle has a tank which can be filled with air coming from a compressed air tank. Water is drained from the tank when it is filled with air and more positive buoyancy is generated. There are also vehicles that use only one thruster for propulsion and do not have a variable buoyancy system (Cavallo & Michelini, 2004; Maurya et al., 2007). The vehicle described in (Cavallo & Michelini, 2004) uses a robotic wrist to position the thruster. This enables the vehicle to move horizontally and vertically. The vehicle is not able to move vertically without moving horizontally; however it is able to do vice versa. The vehicle described in (Maurya et al., 2007) cannot move vertically either without moving horizontally (again, vice versa it can), but instead of using a robotic wrist, it uses diving planes to move vertically.

5. Sensors and instrumentation

As described in Section 3 it is essential for an AUV to know its current position. In order to calculate that position a number of sensors are necessary. The most common sensor is a pressure sensor, it is used to measure the external pressure experienced by the vehicle. This pressure can be converted to a depth (Williams et al., 2006). For dead-reckoning navigation the vehicle speed is needed. There are numerous ways to measure the speed of the vehicle. Usually the velocity is measured using a compass and a water speed sensor. In (Modarress et al., 2007) a sensor is described which can measure the speed of the vehicle using particles that are present in the water. The speed of the particles is measured with diffractive optic elements. Small particles pass through two parallel light sheets and scatter light. The scattered light is collected and the speed of the particles is computed using the time-of-light

and the physical separation of the two light sheets. The sensors are small, very accurate and insensitive for temperature changes and water pressure (Modarress et al., 2007). The problem with these techniques is that sea currents can add velocity components which are not detected by the speed sensor (Leonard et al., 1998).
For operations near the seabed, Doppler velocity logs (DVLs) can be used to measure the vehicle's velocity with respect to the ground. With these measurements the accuracy of the position estimation by the Kalman filter can improve greatly (Leonard et al., 1998; Lee et al., 2007). A DVL measures the Doppler shift of sonar signals reflected by the ground to obtain the velocity (Keary et al., 1999). The system becomes less accurate at low speeds. The correlation velocity log (CVL) is based on the same principle as the DVL, but emits two pulses in close succession. The echoes from the seabed are compared and used to calculate the velocity. This technique is more accurate at low speeds (Keary et al., 1999). Both systems are not influenced by sea currents.
The inertial navigation system (INS) uses accelerometers and gyroscopic sensors to detect the acceleration of the vehicle (Stutters et al., 2008). The measurements are not influenced by sea currents and are therefore more accurate. However, the system is more expensive than the velocity sensors (Leonard et al., 1998). INSs used to be equipped with mechanical gyroscopes. The latest INS uses laser gyroscopes or fiber optic gyroscopes that have no moving parts. This means no friction, leading to more accuracy. In (Fauske et al., 2007) sensor fusion is used to provide more accuracy to the INS. An error-state Kalman filter estimates the drift of the inertial sensors, using external information as measurement, e.g. a DVL and position updates by a mother ship, see Figure 4. With the use of more sensors for a number of parameters, a higher accuracy is achieved (Majumder et al., 2001).
Another aspect for which sensors are needed is obstacle detection. The vehicle must be able to detect obstacles before crashing into them. According to (Majumder et al., 2001) underwater cameras and active sonar are two of the most common sensors for obstacle detection. (Majumder et al., 2001) also states that there should always be at least two sensors, because in a sub-sea environment the information from one sensor can be of poor quality. Therefore, in the technique proposed both the information from the sonar and the camera are used for obstacle detection. Ultrasonic/acoustic sensor systems allow detection of objects far beyond the range of video. Current AUVs detect objects with long range sonar. Lower frequency waves suffer less attenuation in water than higher frequencies. However, the resolution for imaging sonars is better at higher frequencies (Toal et al., 2005).
In (Toal et al., 2005) a new technique is proposed using optical fibers for object detection. Two different sensors are used: one provides information without contact, the other provides information using contact with the object. The first is an extrinsic sensor which transmits light from the sensor end, if there is an object the light will reflect and received by a detector. The second sensor is an intrinsic sensor which does not transmits the light but contains the light within the fiber. A deformation of the fiber, so if the fiber touches an object, has a detectable effect on the light within the fiber. The vehicle described in (Williams et al., 2006) has two sonars. One is used for the determination of depth and obstacle detection. The other is an imaging sonar, which is used to build a map of the environment.

The main sensors for an AUV are a depth sensor, a compass and a speed sensor. With these sensors the vehicle can estimate its position. It is desirable to equip the vehicle with a Doppler velocity log to increase the accuracy of the estimates. Inertial navigation systems with laser or fiber optic gyroscopes are more expensive but also more accurate than the standard speed sensors. Sonar, underwater cameras or optical fibers can be used for obstacle detection.

6. Power supply

As mentioned in Section 1 an AUV must contain its own power. The most common power supply for AUVs is batteries (Smith et al., 1996). A number of AUVs use fuel cells for their power supply (Takagawa, 2007; Haberbusch et al., 2002) and a few use solar power (Jalbert et al., 2003). The advantages of using an electric propulsion over thermal propulsion are silent operation, ease of speed control and the simplicity (Smith et al., 1996).

The silver zinc battery was the most used power source in AUVs for 40 years (Smith et al., 1996; Winchester et al., 2002). But due to recent developments in lithium-ion batteries this has changed (Wilson & Bales, 2006). In (Bradley et al., 2001) different sorts of batteries are summarized. Batteries can be either primary or secondary, meaning non-rechargeable and rechargeable respectively. Most batteries described in the paper are secondary because the majority of batteries in AUVs are rechargeable. Primary batteries usually have a better endurance than secondary, but are more expensive in use.

The most common primary battery is alkaline. It is cheap and easy to work with. However they outgas hydrogen and are temperature sensitive. The lithium primary battery has a very high energy density, but is expensive. Of the secondary batteries lead acid cells are the easiest to work with, but they also leak hydrogen. Nickel cadmium cells are well known and have a flat discharge curve, but it is difficult to determine the state of charge. Nickel zinc cells have a good cycle life and a good energy density. Lithium-ion cells have the highest energy density of the secondary cells. However the circuitry to operate them in a system is complex. Silver zinc cells can handle high power spikes, but are expensive and have a very limited cycle life. As stated before the developments in the technology for lithium-ion batteries made them an attractive alternative to the silver zinc batteries (Wilson & Bales, 2006).

An overview of the batteries and their characteristics is given in Table 2. Usually every load has its own inverter which is powered directly from the main bus (Bradley et al., 2001), as opposed to the situation where the batteries powers several inverters that generate the voltages needed by the different components. This is because inverters are inexpensive and efficient.

Takagawa (Takagawa, 2007) describes a fuel cell for the power supply of the AUV. The fuel cell has a fairly larger capacity than batteries, but the problem with the system is that it is required to be installed in pressure vessels. Also proposed is a mechanism similar to the pressure compensation mechanism used in batteries, for the fuel/oxidant container. The system is small compared to systems using pressure resistant containers. Hydrogen peroxide has already been used with pressure compensation mechanism and is therefore chosen as oxidant, methanol is selected as fuel. The system can be used for underwater vehicles with a very long cruising capability (~10, 000km). The fuel cells can also reduce the logistics burden of the vehicle if the fuel and oxidant are stored in a high density format. Fuel cells that operate on hydrogen and oxygen are attractive power sources for AUVs because they are efficient, quiet, compact and easy to maintain. The total energy delivered by a fuel cell is limited only by the available fuel and oxygen (Haberbusch et al., 2002).

In (Jalbert et al., 2003) an AUV is described that operates on solar power. The main advantage is of course that the vehicle can stay in the water for months without having to be recharged. The vehicle surfaces daily to recharge its lithium-ion batteries.
The most commonly used power supply for AUVs nowadays is lithium-ion batteries. If a long operation time is required fuel cells are a good alternative. For very long operation times, solar power in combination with lithium-ion batteries is a good choice.

Chemistry	Energy density (Whr/kg)	Outgassing	Cycles	Comments
Alkaline	140	Possible, at higher temperature	1	Inexpensive, easy to work with
Li Primary	375		1	Very high energy density
Lead Acid	31.5	Yes	~100	Well established, easy to work with
Ni Cad	33	If overcharged	~100	Very flat discharge curve
Ni Zn	58.5	None	~500	Emerging technology
Li Ion	144	None	~500	Complex circuitry
Silver Zn	100	Yes	~30	Can handle very high power spikes

Table 2. Battery chemistries and their characteristics (Bradley et al., 2001)

7. Canterbury AUV

7.1 Background

As more than half of our oceans are deeper then 3km, one direction of the AUV developments is to explore deep waters. However, development of such AUVs imposes extreme design specifications for the hardware (Uhrich & Watson, 1992), incurring an unaffordable cost for most labs. By contrast, AUVs for shallow waters recently have gained more attention because of their potentially wide use combined with affordable cost. At the University of Canterbury, an AUV prototype has been recently designed with the primary purpose for inspecting and cleaning the sea chests of ships (Figure 6a), an application with significant impact in the area of bio-security.
Sea chests are the intake areas in the hulls of ships for seawater used for ballast, engine-cooling and fire-fighting. Grates on the outside of the chests prevent large organisms from being entrained in the water but many smaller organisms (Figure 6b) survive in the sea chests and are transported around the world creating a bio-security risk. The New Zealand government has placed a high priority on the development of systems and tools to protect native flora and fauna against invasion by unwanted foreign organisms.

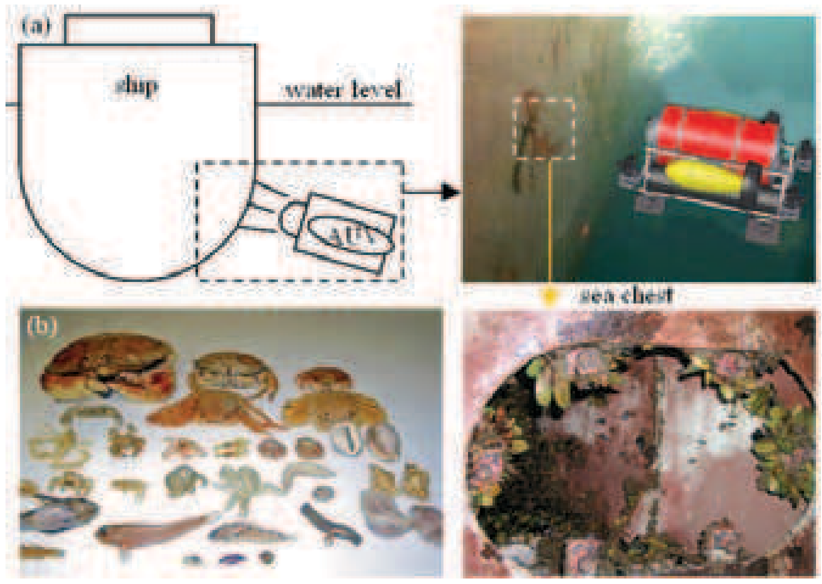


Fig. 6. Autonomous underwater vehicle inspecting and cleaning sea chest of ships. (a) The diagram of the AUV working on the sea chest of the ship. (b) A range of foreign invaders hiding in the sea chest.

To optimize the knowledge of, and reaction to, this threat, the first task is to inspect the sea chests and collect information about the invaders. Currently, divers are sent to do the job, which has inherent problems, including: i) high cost, ii) unavailability of suitably trained personnel for the number of ships needing inspection, iii) safety concerns, iv) low throughput, and v) unsustainable working time underwater to do a thorough job. To reduce the working load of divers and significantly accelerate inspection and/or treatment, it would be highly desirable and efficient to deploy affordable AUVs to inspect and clean these ship sea chests. Thus, this paper presents a low cost AUV prototype emphasizing the unique design issues and solutions developed for this task, as well as those attributes that are generalizable to similar systems. Control and navigation are being implemented and are thus not covered here.

7.2 Hull design

Figure 7. shows the AUV prototype (weighing 112kg, positively buoyant), which consists of basic components, including main hull, two horizontal propellers, four vertical thrusters, two batteries, an external frame, and electronics inside the main hull. This section focuses on the hull design.

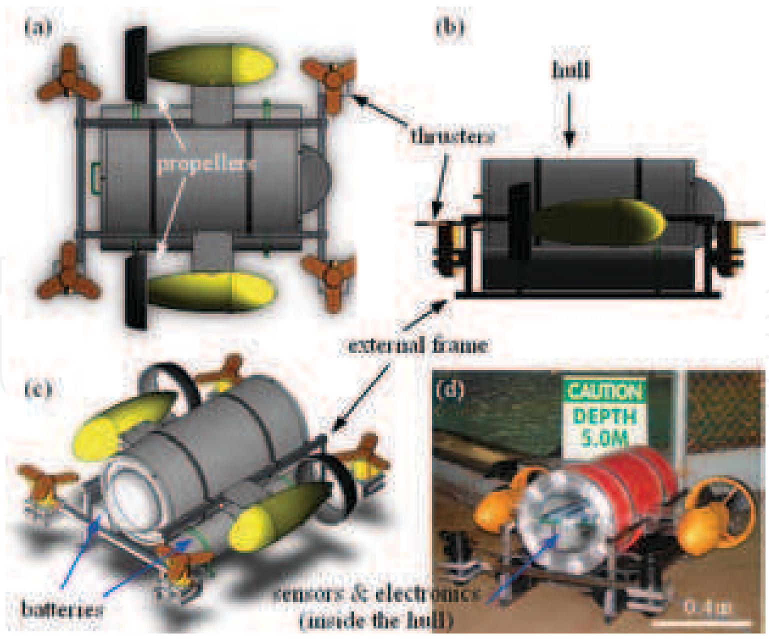


Fig. 7. The hull structure of the vehicle. (a)-(c) Design drawings of the vehicle: (a) Top view. (b) Side view. (c) Isometric view. (d) Real picture of the in-house made vehicle

The foremost design decision is the shape of the hull. Inspired by torpedoes and submarines, a cylindrical hull has been selected. A cylinder has favourable geometry for both pressure (no obvious stress concentrations) and dynamic reasons (minimum drag). To make the hull, three easily accessible materials were compared. The first option is to use a section of highly available PVC storm water pipe. The second option involves having a hull made from a composite material, such as carbon fibre or fibre glass. Mandrel spinning of such a hull will allow more freedom in radial dimensions. The process can in fact incorporate a varying radius along the length resulting in a slender, traditional hull. However, this process requires a large amount of design and set up time. A less desirable third option is to use a section of metal pipe, which is prone to corrosion and has a high weight and cost. As a result, the PVC storm water pipe option was selected.

Two caps were designed to complete the hull, and are attached to each end of the pipe such that they reliably seal the hull. The caps also allow access to the interior for easy repair and maintenance. The end cap design incorporates an aluminium ring permanently fixed to the hull and a removable aluminium plug. The plug fits snugly into the aluminium ring. Sealing is achieved with commercially available O-rings. Sealing directly to the PVC hull would have been more desirable; however this option was not taken for two main reasons. First, PVC does not provide a sealing surface as smooth and even as aluminium and is extremely hard to machine in this case due to the size of the pipe. Second, the PVC pipe is not perfectly round and subject to significant variability, which would make any machined aluminium cap subject to poor fit and potential leakage, decreasing reliability.

The design choices made can thus better manage these issues. More specifically, the design is based on self-sealing where greater outside pressures enforce greater connection between the cap, seals, and PVC hull portion. The O-ring seal employed is made of nitrile, which is resistant to both fresh and salt water.

7.3 Propulsion and steering

The design incorporates 2 horizontal thrusters mounted on both sides of the AUV to provide both forward and backward movement. Yaw is provided by operating the thrusters in opposing directions. The thrusters are 12V dive scooters (Pu Tuo Hai Qiang Ltd, China) that have a working depth of up to 20m.
The dive scooters are lightly modified to enable simple attachment to the external frame of the AUV. The thruster mounts consist of two aluminium blocks, which, when bolted together, clamp a plastic tab on each thruster. These clamps provide a strong, secure mount that can be easily removed or adapted to other specifications.
The force that can be generated by the thruster is characterized, as shown in Figure 8. The significant linearity between the thruster force and the applied duty cycle will significantly facilitate the design and implementation of any control scheme.

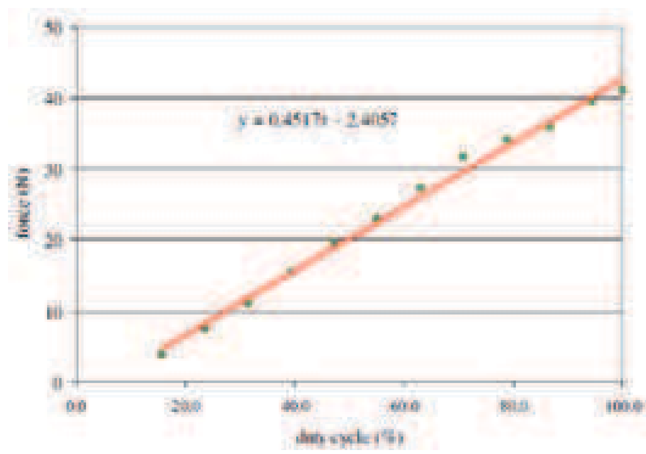


Fig. 8. Calibration of the motor: force with respect to duty cycle

A fluid drag force model is established to evaluate the speed that the AUV can achieve. Figure 9. shows the relationship between the drag forces with respect to the relative velocity of the vehicle. Under the full load of the two thrusters, the vehicle is able to achieve a maximum forward or backward speed of 1.4m/s (~5km/hour).

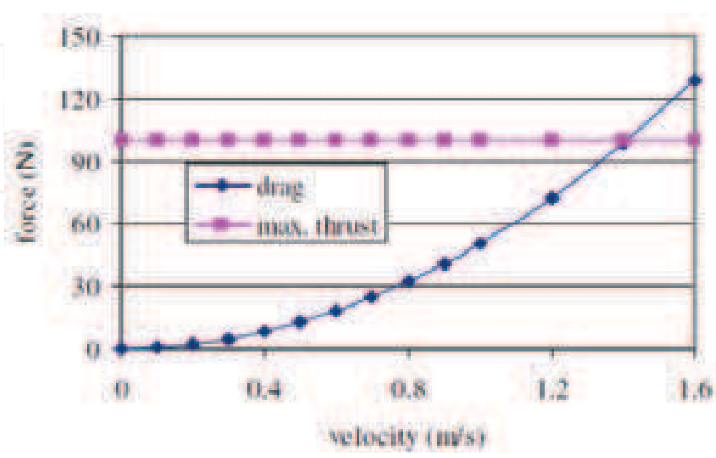


Fig. 9. Drag force of the AUV with different velocities

7.4 Ballast and depth control

Selection of a suitable ballast system is dependent on various factors, such as design specifications, size and geometry of the AUV hull, depth required, and cost. In this design, the hull is made of a PVC pipe with an outer diameter of 400mm and a length of 800mm. The required working depth is 20m. Hence, the ballast system selected not only has to meet the basic requirements enumerated above, but must also be able to fit in the hull. Preferably, all are at a relatively low cost.

First, installing two (2) 160mm inner diameter ballast tanks of 250mm length provides a net force of ±5kg. Additionally, the force required to actuate the piston head at 20m is calculated to be approximately 6000N. To generate such force on the piston head, a powerful linear actuator is needed. The specific linear actuator (LA36 24V DC input, 6800N max load, 250mm stoke length) can be sourced from Linak Ltd in New Zealand. However, the linear actuator has a duty cycle of 20% at max, which means that for every 20s continuous work, it must remain off for 80s before operating again, allowing the AUV to float uncontrolled. In addition, the cost of one linear actuator is US$1036, which would imply that similar actuators with longer duty cycles would cost a larger amount at this time.

Taking the second option, a hydraulic pumping system can be customized from Scarlett Hydraulics Ltd, New Zealand. The overall system has dimensions of 500mm × 250mm × 250mm. It consists of a 1.2KW DC motor, a pump, a 4L hydraulic fluid tank, two dual solenoid valves and two cylindrical tanks. This system meets the required specifications, but has some drawbacks. In particular, it occupies too internal space of the hull, and weighs approximately 20kg (a significant addition of weight). In this case, the overall hydraulic pumping system will cost up to approximately US$2264.

The third option air compressor system is cost effective and is easy to operate by controlling the vent and blow valves. However, the lack of accuracy in controlling compressed gas is a major disadvantage. In addition, performance and operating time are limited by the amount of stored gas. In this design, a 10L tank would be needed to fulfil the changes in buoyancy. In other words, a gas cylinder containing 10L of air compressed to at least 3bar is required for a single diving and rising cycle. Hence, to refill the gas cylinder, the AUV must float to the waters surface before all the air runs out or risk being lost. Regarding the on-site requirement that the AUV should operate for hours, the air tank must either be much bigger or far more highly pressurize, which leads to safety issues.

The fourth option thrusters are different from the previous three systems that all had to be installed inside the AUV. In contrast, thrusters can be attached externally. Hence, sealing is not as critical as it is for the other concepts. If the vehicle is trimmed positively buoyant, it is also reasonably fail-safe, unlike the other three methods. Additionally, the thrusters can be sourced from Pu Tuo Hai Qiang Ltd, Zhou Shan, China for US$55/unit, a reduction of 12-20× in cost if two are used. Each thruster fits in a 215mm × 215mm × 80mm box, and is driven by a 12V DC motor with a max thrust force of 5kg under water. By mounting the desired number of thrusters, a wide range of motions can be controlled, such as pitch and roll control.

Finally, each concept has its own advantages and disadvantages. Comparisons are summarized in Table 3. In this design, the major driving factors for the selection of ballast system are the cost and reliability. Piston ballast tank and thruster systems are reliable since these two depth control methods have been widely employed in most autonomous underwater vehicle development. Considering the cost, the thruster system is more effective. Hence, the thruster system is chosen as the final design.

	Diving Tech	Installation	Buoyancy	Sealing	Reliability	Overall Cost *
Piston ballast tanks	Static	Internal	+ ve, - ve, Neutral	Difficult	Used in most remote submarines	$2500
Hydraulic pumping system	Static	Internal	+ ve, - ve, Neutral	Difficult	Not reliable	$2710
Air compressor	Static	Internal	+ ve, - ve, Neutral	Difficult	Air on board is limited, compressed air hard to handle	$420
Thrusters	Dynamic	External	+ ve	None	Used in most ROVs with big size	$500

Table 3. Ballast comparison. * The cost is estimated as an overall system

There are four thrusters vertically mounted around the AUV with one at each corner (See Figure 7). Mounting four thrusters produces a total of 20kg thrust force at full load, and allows a wide range of motion control. They enable the control of not only the vertical up and down motion, but pitch and roll motions. To achieve this control, each thruster is connected to a speed control module that can be controlled via a central microprocessor. By inputting different digital signals, various forces thus speeds are generated. Therefore, desired motion control can be obtained by different combinations.

7.5 Electronics and control

7.5.1. Power supply

For long term operation, this design must locate the power supply on-board, unlike many current models that receive power over an umbilical link (Chardard & Copros, 2002). Since all the systems onboard the AUV are electric, sealed lead acid batteries are chosen for the power supply. These batteries have high capacity and can deliver higher currents, than other types of rechargeable battery (Schubak & Scott, 1995; Bradley et al., 2001). They are stable, inexpensive, mechanically robust and can work in any orientation, all of which are important considerations in a vehicle of this type. To supply enough current for the entire machine several batteries have to be joined together. Instead of adding dead weight to achieve neutral buoyancy extra batteries can be added as needed so that the total operating time of the AUV is higher than that required for a given application.

It is also highly desirable to locate the battery compartments separate from the main hull so that they can be interchanged in the field without opening the sealed main hull. To accommodate this requirement two tubes are fitted below the hull to house batteries. Within these tubes the batteries are connected to two bus bars. Each battery is fused prior to connecting to the bus bar, and the bars are isolated to the greatest extent possible to increase safety. These bus bars are then wired into the main hull, where a waterproof socket enables the quick interchange of battery compartments. A similar bus system exists inside the hull with connections to motors and electronic power supplies. Each of these internal connections is similarly fused. Longer term, it would be desirable to intelligently monitor the bus to track the state of each battery and overall power consumption.

7.5.2. Central processing unit

The central processing unit is responsible for accessing sensors, processing data and setting control outputs such as motor speeds. Several systems are considered for this unit, an embedded system using microprocessors, FPGAs or a small desktop PC. A microprocessor system, most likely based on an ARM processor would have low cost, size and power requirements and is easy to interface to both analogue and digital sensors, motors and other actuators. The processing power and memory allocations of these microprocessors are all more than sufficient for the simple control tasks likely to be required, but would struggle with larger sensor or processing tasks, such as image processing. An FPGA system would also be small and have low power requirements, but would be more expensive. While FPGAs work very well for fast, complex processing tasks such as image processing, their complexity in design and programming necessitates their use in parallel with other more flexible CPU choices. The last system considered is a small desktop PC. Although a desktop PC is bigger, more expensive and consumes more power than either of the prior two options, it provides immense processing power, memory and a diverse range of peripherals. It is therefore chosen in this initial design for the following primary reasons:

- Added power requirements were not an issue since we have a sizeable power supplies.
- Processing power is more than adequate for this initial design and future developments.
- Large volumes of memory are available, both volatile for program execution and solid state for storage of gathered data.
- Despite not having direct access to sensors and control units, a diverse range of peripherals available can be used, including USB, RS232 and Ethernet, enabling a potentially greater range of sensors and sensor platforms for developing broad ranges of specific applications.
- A USB module is already provided for a webcam for initial image sensing applications and an Ethernet module is provided for remote connection.

An AMD Sempron 3000+ processor and ASUS M2N-PV motherboard are used for this purpose. These models have lower power requirements and heat generation. Software interfaces this unit with sensors and motor controllers, as well as to a remote control PC. An automotive power supply (Exide, Auckland, NZ) is used to provide power for the computer. It takes a 12V DC input and converts it to the ATX standard power supply required by the PC. This module is also designed to be used in an electrically noisy and hostile environment and is ideally suited the specific design situations considered.

7.5.3. Sensors

When the AUV is used autonomously, after development there will be a large and extensive sensor suite onboard. Currently, the sensors onboard measure

- water pressure, from which depth can be determined
- water temperature, inner hull temperature and humidity
- the AUV position in the three principal axes: yaw, pitch and roll
- visual or digital image feedback via a webcam.

Submersible pressure sensors that are salt water tolerant and can measure up to the pressures required are difficult to acquire at low cost. The sensor chosen was sourced from Mandeno Electronics for US$121. This sensor measures up to twice the depth required, and outputs an analogue output between 0 and 100mV. Thermocouples from Farnell Electronics (Christchurch, New Zealand) are used to measure the water temperature, and provide an analogue output relative to the temperature difference between the two ends of the thermocouple. TMP100 sensors (Texas Instruments) are used to measure the base temperature of the thermocouple, and the hulls interior temperature. These sensors give a digital output using the I2C protocol. A HF3223 humidity sensor (Digi-Key) is used to measure humidity inside the hull. A MMA7260QT accelerometer (Freescale Semiconductor) is used to calculate orientation. The accelerometer has a 0-2.5V analogue output. The connection of the sensors is shown in Figure 10.

To eliminate signal noise, An Atmel AT90USB82 microprocessor is connected to the USB ports of the computer to move all noise sensitive data to the acquisition points. The analogue sensors are amplified using an INA2322 instrumentation amplifier, if necessary, and read by an ADS7828 analogue to digital converter. This converter is then connected to the Atmel microprocessor using a common I2C bus with the TMP100. The humidity sensor is attached to a clock input which converts the frequency based signal to a humidity based reading. The microprocessor performs some basic processing on this data, temperature compensating the pressure sensor and thermocouple, and calculating yaw, pitch and roll from the accelerometer readings.

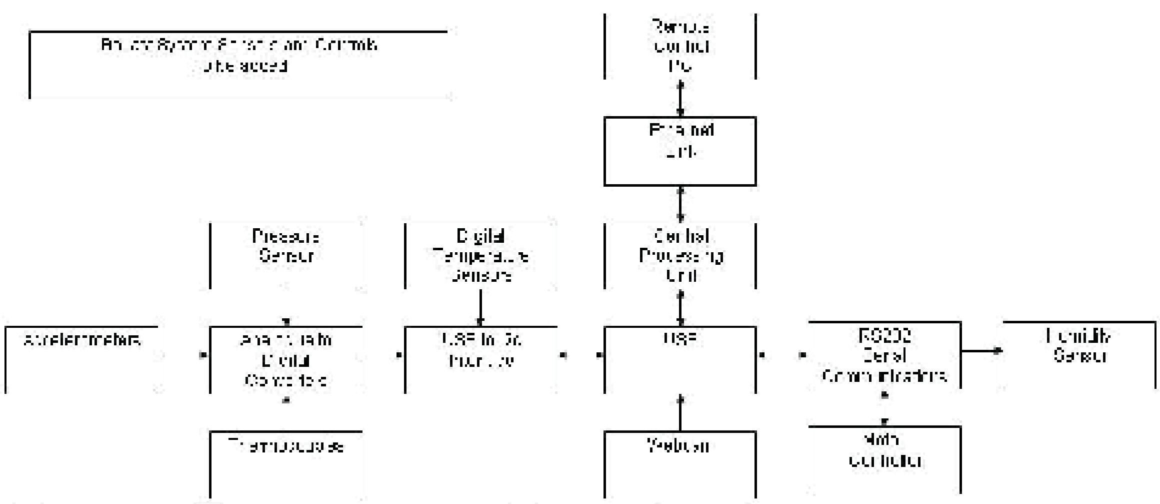


Fig. 10. The block diagram for electronic systems and control

Visual or digital image sensing is included via a Logitech webcam connected directly to the on-board computers USB port. The video stream can be sent back over a wireless remote control network connection to the remote PC. At this stage, no image processing is done on this stream on-board, and it is included purely to assist in manual control of the AUV at this time, and for use in later application development.

7.5.4. Propulsion motor driver

For the six motors (two for horizontal propulsion, and four for vertical ballast control), three (3) RoboteQ AX2500 motor controllers are used for control. Each controller is able to control two motors up to 120 amps, much higher than the 25 amps needed by the motors selected. The controllers are controlled via RS232 (serial port) interfaces, which are already available on the computer motherboard. Computer control of the controllers is easily achieved through a LabView or MATLAB interface, either manually or automatically, where both interfaces have been implemented to allow greater user ease of use.

7.5.5. Control system and communications

During testing and development, remote control is required for the AUV. Sensors readings need to be sent to a user, and control signals sent back to the AUV. Displaying the video feed from the webcam is also desired to provide the operator with visual feedback. High frequency radio transmissions are impossible underwater due to the high losses encountered during the air/water boundary (Leonessa et al., 2003). Lower frequency transmissions could have been used to communicate with the AUV, but they do not possess enough bandwidth to send the required data. An umbilical Ethernet cable is being used for this remote link between the AUV and an external control computer for this development phase. Figure 6. shows the electronics and control structure. Note that in an actual, developed application, or final development thereof, the robot will be acting autonomously and this umbilical will not be required.

8. Conclusions and future work

AUVs have a lot of potential in the scientific and military use. With the development of technologies, such as accurate sensors and high density batteries, the use of AUVs will be more intensive in the future. In this book chapter, several subjects of an AUV have been reported. For every subject some of the techniques used in the past and the techniques used nowadays are described. For every aspect a suitable technique for an AUV is given. To show how the state-of-the-art technologies could be used in AUVs, an AUV prototype developed recently at the University of Canterbury has been detailed in design.

The AUV was specially designed and prototyped for shallow water tasks, such as inspecting and cleaning sea chests of ships. It features low cost and wide potential use for normal shallow water tasks with a working depth up to 20m, and a forward/backward speed up to 1.4m/s. Each part of the AUV is deliberately chosen based on a comparison of readily available low cost options when possible. The prototype has a complete set of components including vehicle hull, propulsion, depth control, sensors and electronics, batteries, and communications. The total cost for a one-off prototype is less than US$10,000. With these elements, a full range of horizontal, vertical and rotational control of the AUV is possible including computer vision sensing. The overall underwater vehicle will be a good platform for research, as well as for its specific applications, many of which are growing in importance like the sea chest inspection case noted here.

The controls of the vehicle are under development. The vertical motion control uses the feedback from the pressure sensor, while the horizontal motion control uses an inertial measurement unit (Microstrain GX2 IMU, VT, USA) to get information about the vehicle attitude and acceleration. The fluidic model (dynamic drag force) of the vehicle will be established by simulation and verified by experimental measurement. This model would be integrated in the control and navigation module of the vehicle.

9. References

Allmendinger, E. (1990). *Submersible Vehicle Systems Design*. Jersey City, NJ: Society of Naval Architects and Maringe Engineers, 1990.

Ballard, R. (1987). *The Discovery of the Titanic*. New York, NY: Warner/Madison Press Books, 1987.

Blidberg, D. (2001). The development of autonomous underwater vehicles (AUV): a brief summary, *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA2001)*, Seoul, Korea, May 2001.

Bradley, A.; Feezor, M.; Singh, H. & Sorrell, F. (2001). Power systems for autonomous underwater vehicles, *IEEE Journal of Oceanic Engineering*, Vol. 26, No. 4, 526–538.

Caccia, M. (2006). Autonomous surface craft: prototypes and basic research issues, *14th Mediterranean Conference on Control and Automation*, June 2006.

Cavallo, E. & Michelini, R. (2004). A robotic equipment for the guidance of a vectored thrustor AUV, *35th International Symposium on Robotics ISR 2004*, 2004.

Chardard, Y. & Copros, T. (2002). Swimmer: final sea demonstration of this innovative hybrid AUV/ROV system, *Proceedings 2002 International Symposium on Underwater Technology*, Tokyo, Japan, Apr. 2002, 17-23.

Curtin, T. & Bellingham, J. (2001). Autonomous ocean-sampling networks, *IEEE Journal of Oceanic Engineering*, Vol. 26, 421-423.

Evans, J. & Meyer, N. (2004). Dynamics modeling and performance evaluation of an autonomous underwater vehicle, *Ocean Engineering*, Vol. 31, 1835-1858.

Fauske, K.; Gustafsson, F. & Hegrenaes, O. (2007). Estimation of AUV dynamics for sensor fusion, *10th International Conference on Information Fusion 2007*, 1-7, July 2007.

Feng, Z. & Allen, R. (2004). Reduced order H1 control of an autonomous underwater vehicle, *Control Engineering Practice*, Vol. 12, 1511-1520.

Fossen, T. (1994). *Guidance and control of ocean vehicles*. New York: John Wiley and Sons Ltd., 2-nd ed., 1994.

Fryxell, D.; Oliveira, P.; Pascoal, A.; Silvestre, C. & Kaminer, I. (1996). Navigation, guidance and control of AUVs: an application to the MARIUS vehicle, *Control Engineering Practice*, Vol. 4, No. 3, 401-409.

Gaccia, M. & Veruggio, G. (2000). Guidance and control of a reconfigurable unmanned underwater vehicle, *Control Engineering Practice*, Vol. 8, 21-37.

Griffiths, G. & Edwards, I. (2003). AUVs: designing and operating next generation vehicles, *Elsevier Oceanography Series*, Vol. 69, 229-236.

Haberbusch, M.; Stochl, R.; Nguyen, C.; Culler, A.; Wainright, J. & Moran, M. (2002). Rechargeable cryogenic reactant storage and delivery system for fuel cell powered underwater vehicles, *Proceedings Workshop on Autonomous Underwater Vehicles*, 103-109, June 2002.

Horgan, J. & Toal, D. (2006). Review of machine vision applications in unmanned underwater vehicles, *9th International Conference on Control, Automation, Robotics and Vision*, Dec. 2006.

Hsu, C.; Liang, C.; Shiah, S. & Jen, C. (2005). A study of stress concentration effect around penetrations on curved shell and failure modes for deep-diving submersible vehicle, *Ocean Engineering*, Vol. 32. No. 8-9, 1098-1121.

Jalbert, J.; Baker, J.; Duchesney, J.; Pietryka, P.; Dalton, W.; Blidberg, D.; Chappell, S.; Nitzel, R. & Holappa, K. (2003). A solar-powered autonomous underwater vehicle, *OCEANS 2003*.

Jalving, B. (1994). The NDRE-AUV flight control system, *IEEE Journal of Oceanic Engineering*, Vol. 19, 497-501.

Kaminer, I.; Pascoal, A.; Khargonekar, P. & Coleman, E. (1995). A velocity algorithm for the implementation of gain-scheduled controllers, *Automatica*, Vol. 31, No. 8, 1185-1191.

Keary, A.; Hill, M.; White, P. & Robinson, H. (1999). Simulation of the correlation velocity log using a computer based acoustic model, *11th International Symposium Unmanned Untethered Submersible Technology*, 446-454, August 1999.

Kondoa, H. & Ura, T. (2004). Navigation of an AUV for investigation of underwater structures, *Control Engineering Practice*, Vol. 12, 1551-1559.

Lee, P.; Jun, B.; Kim, K.; Lee, J.; Aoki, T. & Hyakudome, T. (2007). Simulation of an inertial acoustic navigation system with range aiding for an autonomous underwater vehicle, *IEEE Journal of Oceanic Engineering*, Vol. 32, 327-345.

Leonard, J.; Bennett, A.; Smith, C. & Feder, H. (1998). Autonomous underwater vehicle navigation, *Proceedings IEEE ICRA Workshop Navigation Outdoor Autonomous Vehicle*, May 1998.

Leonessa, A.; Mandello, J.; Morel, Y. & Vidal, M. (2003). Design of a small, multi-purpose, autonomous surface vessel, *Proceedings OCEANS 2003*, Vol. 1, San Diego, CA, USA, 2003, 544–550.

Lygouras, J.; Lalakos, K. & Tsalides, P. (1998). THETIS: an underwater remotely operated vehicle for water pollution measurements, *Microprocessors and Microsystems*, Vol. 22, No. 5, 227–237.

Majumder, S.; Scheding, S. & Durrant-Whyte, H. (2001). Multisensor data fusion for underwater navigation, *Robotics and Autonomous Systems*, Vol. 35, 97-108.

Maurya, P.; Desa, E.; Pascoal, A.; Barros, E.; Navelkar, G.; Madhan, R.; Mascarenhas, A.; Prabhudesai, S.; Afzulpurkar, S.; Gouveia, A.; Naroji, S. & Sebastiao, L. (2007). Control of the Maya AUV in the vertical and horizontal planes: theory and practical results, *Proceedings MCMC2006 - 7th IFAC Conference on Manoeuvring and Control of Marine Craft*, 2007.

Modarress, D.; Svitek, P.; Modarress, K. & Wilson, D. (2007). Micro-optical sensors for underwater velocity measurement, *Symposium on Underwater Technology and Workshop on Scientific Use of Submarine Cables and Related Technologies*, 235-239, April 2007.

Monteen, B.; Warner, P. & Ryle, J. (2000). Cal poly autonomous underwater vehicle, California Polytechnic State University, 2000.

Paster, D. (1986). Importance of hydrodynamic considerations for underwater vehicle design, *OCEANS*, Vol. 18, 1413-1422, September 1986.

Ridao, P.; Batlle, J. & Carreras, M. (2001). Model identification of a low-speed AUV, In Control Applications in Marine Systems. *International Federation on Automatic Control*, 2001.

Rife, J. & Rock, S.M. (2002). Field experiments in the control of a jellyfish tracking ROV, in *MTS/IEEE Oceans '02*, Vol. 4, 2002, 2031-2038.

Ross, C. (2006). A conceptual design of an underwater vehicle, *Ocean Engineering*, Vol. 33, No. 16, 2087-2104.

Schubak, G. & Scott, D. (1995). A techno-economic comparison of power systems for autonomous underwater vehicles, *IEEE Journal of Oceanic Engineering*, Vol. 20, No. 1, 94-100.

Serrani, A. & Conte, G. (1999). Robust nonlinear motion control for AUVs, *IEEE Robotics & Autonomation Magazine*, Vol. 6, 33-38.

Smallwood, D. & Whitcomb, L. (2004). Model-based dynamic positioning of underwater robotic vehicles: theory and experiment, *IEEE Journal of Oceanic Engineering*, Vol. 29, No. 1, 169-186.

Smallwood, D.; Bachmayer, R. & Whitecomd, L. (1999). A new remotely operated underwater vehicle for dynamics and control research, *Proceedings UUST '99*, 1999.

Smith, P.; James, S. & Keller, P. (1996). Development efforts in rechargeable batteries for underwater vehicles, *Proceedings Autonomous Underwater Vehicle Technology Symposium, AUV'96*, 441-447, June 1996.

Stachiw, J. (2004). Acrylic plastic as structural material for underwater vehicles, *International Symposium on Underwater Technology*, 289-296, April 2004.

Stutters, L.; Liu, H.; Tiltman, C. & Brown, D. (2008). Navigation technologies for autonomous underwater vehicles, *IEEE Transactions on Systems, Man and Cybernetics, Part C: Applications and Reviews*, Vol. 38, 581-589.

Takagawa, S. (2007). Feasibility study on DMFC power source for underwater vehicles, *Symposium on Underwater Technology and Workshop on Scientific Use of Submarine Cables and Related Technologies*, 326-330, April 2007.

Tangirala, S. & Dzielski, J. (2007). A variable buoyancy control system for a large AUV, *IEEE Journal of Oceanic Engineering*, Vol. 32, 762-771.

Tivey, M.; Johnson, H.; Bradley, A. & Yoerger, D. (1998). Thickness of a submarine lava flow determined from near-bottom magnetic field mapping by autonomous underwater vehicle, *Geophysical Research Letters*, Vol. 25, 805-808.

Toal, D.; Flanagan, C.; Lyons, W.; Nolan, S. & Lewis, E. (2005). Proximal object and hazard detection for autonomous underwater vehicle with optical fibre sensors, *Robotics and Autonomous Systems*, Vol. 53, 214-229.

Uhrich, R. & Watson, S. (1992). Deep-ocean search and inspection: Advanced unmanned search system (AUSS) concept of operation, Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA, Tech. Rep. NRaD TR 1530, Nov. 1992.

Valavanis, K.; Gracanin, D.; Matijasevic, M.; Kolluru, R. & Demetriou, G. (1997). Control architectures for autonomous underwater vehicles, *Control Systems Magazine*, Vol. 17, 48-64.

von Alt, C. (2003). Autonomous underwater vehicles, *Autonomous underwater Langrangian platforms and sensors workshop*, LaJolla, CA, March-April 2003.

Wasserman, K.; Mathieu, J.; Wolf, M.; Hathi, A.; Fried, S. & Baker, A. (2003). Dynamic buoyancy control of an ROV using a variable ballast tank, *OCEANS 2003*, Vol. 5, SP2888-SP2893, September 2003.

Wernli, R. (2001). Low cost AUV's for military applications: Is the technology ready? in *Pacific Congress on Marine Science and Technology 2001*, San Francisco, CA, July 2001.

Willcox, S.; Vaganay, J.; Grieve, R. & Rish, J. (2001). The bluefin BPAUV: An organic wide-area bottom mapping and mine-hunting vehicle, in *Proceedings UUST '01*, 2001.

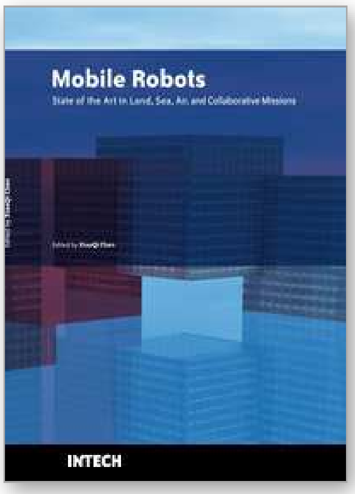
Williams, C. (2004). AUV systems research at the NRC-IOT: an update, in 2004 *International Symposium on Underwater Technology*, 2004, 59-73.

Williams, S.; Newman, P.; Dissanayake, G.; Roseblatt, J. & Durrant-Whyte, H. (2006). A decoupled, distributed AUV control architecture, University of Sydney NSW, 2006.

Wilson. R. & Bales, J. (2006). Development and experience of a practical pressure-tolerant, lithium battery for underwater use, *OCEANS 2006*, 1-5, September 2006.

Winchester, C.; Govar, J.; Banner, J.; Squires, T. & Smith, P. (2002). A survey of available underwater electric propulsion technologies and implications for platform system safety, *Proceedings Workshop on Autonomous Underwater Vehicles*, 129-135, June 2002.

Wolf, M. (2003). *The design of a pneumatic system for a small scale remotely operated vehicle*, Bachalor's Thesis, MIT, May 2003.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