# MICRO AUTONOMOUS UNDERWATER VEHICLE

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# ABSTRACT

Coral reef monitoring project has gained its momentum in the world when the world population starts to realise the effect of global warming and pollution. Constant coral reef monitoring project requires human divers to observe and monitor at a very high frequency to observe the effect of human activities to the coral reef. The usage of autonomous underwater vehicle (AUV) has proven its efficiency and its benefit in reducing the risk and lengthen the monitoring time of coral reef. An existing underwater vehicle with dynamic diving principle is adopted for this research, whereby the electronic components have to be stored on board in a watertight electronics compartment. The design of watertight electronics compartment has been verified with finite element analysis that it is safe to work up to 15m deep. Depth control simulation carried out in Matlab Simulink indicates the depth control of the AUV can be controlled using Proportional–Integral–Derivative (PID) controller. The designed hardware, both mechanical and electronics are fabricated and developed and implemented on the adopted underwater vehicle for validation purpose. Microcontroller is developed to control the AUV through a tether cable.

## ABSTRAK

Projek pemantauan terumbu karang telah mula mendapat perhatian dunia setelah masyarakat mulai sedar kesan pemanasan global dan pencemaran. Projek pemantauan yang berterusan ini memerlukan penyelam-penyelam dalam pemerhatian dan pemantauan yang berfrekuensi tinggi bagi memerhatikan kesan aktiviti-aktiviti manusia terhadap terumbu karang tersebut. Penggunaan kenderaan autonomi selam (AUV) telah terbukti keberkesanannya dalam mengurangkan risiko kerosakan malahan mampu memanjangkan tempoh pemantauan tersebut. Kenderaan selam yang sedia ada digunapakai bagi projek penyelidikan ini, di mana komponen elektroniknya perlu disimpan dalam kotak elektronik yang kedap air. Reka bentuk kotak elektronik ini telah diuji dengan menggunakan analisa unsur terhingga sehinggakan mampu bekerja sehingga kedalaman 15 m. Simulasi kawalan kedalaman yang telah dijalankan dalam Matlab Simulink menunjukkan kawalan kedalaman AUV tersebut boleh dikawal menggunakan pengawal Perkadaran - Integral- Derivatif (PID). Rekabentuk perkakas ini yang mana kedua-dua alat mekanikal dan elektronik telah dibangun dan diletakkan bersama kenderaan selam tersebut untuk tujuan pengesahan. Pengawal mikro turut dibangunkan bagi mengawal AUV melalui kabel penambat.

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| | |
|---|---|
| $C_D$ | Drag coefficient |
| $C_G$ | Center of Gravity |
| $C_B$ | Center of Buoyancy |

# LIST OF ABBREVIATIONS

| | |
|---|---|
| ABS | Acrylonitrile butadiene styrene |
| AIMS | Australia Institute of Marine Science |
| AUV | Autonomous Underwater Vehicle |
| CAD | Computer-Aided-Design |
| CFRP | Carbon Fibre Reinforced Polymer |
| DOF | Degree of freedom |
| DVL | Doppler velocity logs |
| GFRP | Glass Fibre Reinforced Polymer |
| GPS | Global Positioning System |
| INS | Inertial navigation system |
| MMC | Metal matrix composite |
| Li | Lithium |
| PID | Proportional–Integral–Derivative |
| PVC | Polyvinyl chloride |
| PWM | Pulse Width Modulation |
| ROV | Remotely Operated Underwater Vehicle |
| RPM | Revolution per minute |
| VDC | Direct current Voltage |
| 3D | Three dimensional |

# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

The first underwater vehicle "Turtle" was developed in the year 1755 by David Bushnell and Ezra Bushnell in Saybrook, Connecticut and it was able to perform mission for 30 minutes. The introduction of submarine in naval battle catalysed the development of torpedoes, which are regarded as the first Autonomous Underwater Vehicles (AUVs) (Blidberg, 2001).

Non-military submarines generally support underwater investigations and assessment such as seabed mapping, pipeline monitoring, identifying drill sites for oil extraction and coral monitoring. Autonomous Underwater Vehicle (AUV) is defined as an underwater vehicle with its own power source and completes a predefined mission without being controlled by an operator.

The development of commercial AUVs are being spearheaded by Bluefin Robotics and Kongsberg Maritime. Commercial AUVs are large undersea systems that are equipped with complex sensors for various underwater mission. US Navy Bluefin-21 by Bluefin Robotics is designed to submerge to maximum depth of 4500 meters and to operate for 25 hours at 3 knots (1.85 km/h). Recently, it was involved in the search of missing Malaysia Airlines Flight 370 in the Indian Ocean. The usage of AUV in the Indian Ocean has demonstrated the reduction of risk in deep sea mission. On the other hand, Shell Oil Company has estimated to save up $100 million with the usage of commercial AUV in 5 years. (Desa, Madhan, & Maurya, 2006)

Recent development of AUV focuses on the development of group of small, low cost networked autonomous underwater vehicles as well as the search for better power source and external communication technology for AUV.

## 1.2 Background of research

Coral reefs, which are the diverse underwater ecosystems held together by calcium carbonate structures secreted by corals (Wikipedia, 2016), are important as they can protect coastlines from the damaging effects of wave action and provide habitats for marine organisms (Queensland Museum, n.d.). Health of coral reefs is affected by the activities on land that add nutrients and sediments to the ocean (Teach ocean science, n.d.). Many coral reef conservation programme have been implemented in the world to monitor, preserve, sustain and restore valuable coral reef ecosystems.

In Malaysia, a coral reef monitoring project in various location in Malaysia is conducted by Assoc. Prof. Dr. Shahbudin in International Islamic University Malaysia. In Malaysia, natural coral reefs are growing at a depth of 10 to 15 meters from sea level, whereas artificial coral reefs are planted at the depth of 30 to 35 meters. This coral reef monitoring project monitors the growth of the natural coral reefs and artificial coral reefs in the study area by capturing underwater videos.

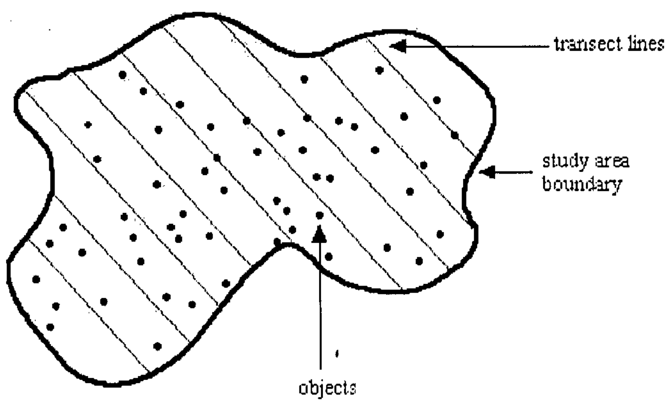


**Figure 1:** Linear transects sampling scheme

Source: (McDonald, 2013)

Each study area is monitored with linear transects sampling scheme and is separated into five transects, each measuring 30.87 meters (100 feet). The transects are predetermined and the diver will follow the transect lines and record underwater videos 0.25 meter above of the coral reefs as shown in Figure 2. The cruising speed of the diver during video recording should not exceed 4 meters per minute to reduce motion blur in the video recordings. The mission, which covers a study area, is usually accomplished by human diving of four to five personnel in a day.

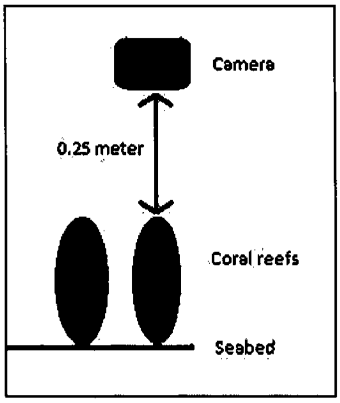


**Figure 2:** Distance of underwater video camera from the coral reefs

Various methods have been employed in the field of coral reef monitoring and assessment in the world as shown in Table 1. These methods require human divers to observe and record underwater video for coral reef monitoring purpose.

**Table 1:** Coral reef monitoring method (Hawai'i Coral Reef Network, n.d.)

| Method | Organisation |
|---|---|
| Crown-of-thorns starfish and coral surveys using the manta tow and scuba search techniques | Australia Institute of Marine Science (AIMS) - Reef Monitoring Research |
| PointCount for Coral Reefs | Phillip Dustan, University of Charleston |
| Rapid Assessment Protocol | Atlantic and Gulf Reef Assessment |
| Reef Check Core Methods | Reef Check |

In recent years, autonomous underwater vehicle has been utilised to perform coral reef monitoring. Hence, the coral reef monitoring project by Assoc. Prof. Dr. Shahbudin is planning to invest in an autonomous underwater vehicle to perform regular coral reef monitoring as it is known to reduce risk in monitoring project, reduce manpower needed, reduce time needed to cover a study area and increases the frequency of coral reef monitoring per year.

## 1.3 Problem statement

Coral reef monitoring project by Assoc. Prof. Dr. Shahbudin requires human diving to observe and record underwater video containing the coral reef in the study area. Limitation of human diving time and the fitness level of the divers will affect the time taken for each study area. Human divers involved in this project is only given a maximum diving time of 1 hour per dive, which includes ascending and descending time. According to Assoc. Prof. Dr. Shahbudin, each transects could take up to 1 hour due to diving preparation and change of location. Human divers are generally given 15 minutes break before the next dive. The standard schedule of coral reef monitoring project for 1 day is summarised in Table 2.

**Table 2 :** Schedule of coral reef monitoring project for 1 day

| Time | Activity |
|---|---|
| 8.30am – 9.30am | Study Area 1 - Transect 1 (Dive 1) |
| 9.30am – 9.45am | Rest time for divers and location change |
| 9.45am – 10.45am | Study Area 1 - Transect 2 (Dive 2) |
| 10.45am –11.00am | Rest time for divers and location change |
| 11.00am – 12.00am | Study Area 1 - Transect 3 (Dive 3) |
| 12.00am – 2.00pm | Lunch Break |
| 2.00pm – 3.00pm | Study Area 1 - Transect 4 (Dive 4) |
| 3.00pm – 3.15pm | Rest time for divers and location change |
| 3.15pm – 4.15pm | Study Area 1 - Transect 5 (Dive 5) |

On the other hand, human diving is weather and sea condition dependent. Malaysia experiences two monsoon seasons in a year, in which Southwest Monsoon is from May till September and Northeast Monsoon is from October till March. The locations of study in the coral reef monitoring project experience one monsoon season per year. During monsoon season, the locations of study that experience monsoon wind will not be monitored due to rough sea condition.

In addition, the number of divers increases with the number of tasks to be accomplished. Light intensity in the water, suspended sediments concentration, water temperature, salinity of water and pH of water are among the tests that must be measured during the monitoring work in each transect. Another diver would be needed when sample collection of seabed substrate is to be carried out. The divers require training before the monitoring project as they need to know the coral life form so that the monitoring project can be done more efficiently.

## 1.4 Objectives of research

The objectives of this research are:

i. To design and build watertight electronics compartment for micro AUV.
ii. To design electronic circuit for navigation of micro AUV.
iii. To develop microcontroller for the navigation of micro AUV.

## 1.5 Scopes of research

The project consists of two main parts, which are watertight electronics compartment development, electronic system development and microcontroller development. The scope and limitations of this project are as follows:

i. Develop and build low-cost watertight electronics compartment for micro AUV that can operate up to 15 m.
ii. Design and develop electronic circuit for all sensory and actuation, which includes waterproof cable connection.

iii. Simulate depth control of micro AUV using Proportional–Integral–Derivative (PID) controller.

iv. Develop microcontroller for basic control of micro AUV.

## 1.6 Thesis outline

This thesis consists of five chapters. The first chapter provides a general introduction of autonomous underwater vehicle and coral reef monitoring project, as well as addressing the need of autonomous underwater vehicle to replace conventional coral reef monitoring by scuba diving. This chapter will include objectives and scopes of the project, which will define the following methodology and results.

Chapter 2 consists of literature review on AUV structure, navigation and control of AUV, propulsion, dive and buoyancy, sensors and instrumentation and power supply of the AUV. The literature review will be further used as reference to the methodology of this project.

Chapter 3 provide an overview of methodology of this project. There are four main project phases which are development of electronics circuit for the micro AUV, development of watertight electronics compartment for micro AUV, simulation of depth control of micro AUV using Proportional–Integral–Derivative (PID) controller and the controller development for micro AUV.

Chapter 4 will then discuss the results obtained from this project throughout the four main project phases, in terms of simulation and hardware implementation.

Lastly, chapter 5 concludes this project and discusses the challenges and possible future works to further improve this micro AUV.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

This chapter reviews the important parameters of AUV structure, navigation and control of AUV, propulsion, dive and buoyancy, sensors and instrumentation and power supply of the AUV.

## 2.2 AUV Structure

The hull is deemed as one of the most important aspects in the design and built of an AUV. There is a number of approach that could be taken in the design of the hull, nonetheless the designs are primarily dependent of the specific task of the AUV (Allemendinger, 1990). However, there are a general guideline that must be taken into consideration in the hull design, namely depth required, structural integrity, practicality, restrictions for future additions and size requirements.

The target depth influences the hydrostatic pressure that the AUV experiences, therefore the design must be able to withstand the aforementioned pressure. Amongst the design shapes that have been employed are spherical (Paster, 1986) and circular cylindrical (Ross, 2006). However, it is noteworthy to mention that although the former shape is better in withstanding pressure, its stability is rather compromised. The latter design is much more prominent and has been used extensively in both scientific research and in military (Evan, J;Meyer, 2004) due to its desirable hydrodynamic form and exceptional pressure resistance.

Drag minimisation is also non-trivial in the design of the hull as it would affect the power utilisation of the AUV. Therefore, it is desirable to have a hull design that has a minimum drag coefficient. Furthermore, Paster (1986) reported that a good hydrodynamic design which results to a desirable drag may improve the AUV range up to 10 times.

Material selection of the hull has to strike balance between good corrosion resistance, affordability as well as high strength to weight ratio. Over the years, a number of materials ranging from steel-based, composites, acrylic and even plastics (Ross, 2006) and (Stachiw, 2004) has been utilised and investigated in the design of hull. Table 3 summarises the properties of materials that has been utilised.

**Table 3:** Material Properties, from (Ross, 2006) and (Stachiw, 2004)

| Material | Density (kg/m$^3$) | Yield Strength (MPa) |
|---|---|---|
| High strength Steel (HY80) | 7860 | 550 |
| Aluminium alloy (7075-6) | 2900 | 503 |
| Titanium alloy (6-4 STOA) 4.5 830 120 184 | 4500 | 830 |
| GFRP (Epoxy/S-lass) | 2100 | 1200 |
| CFRP (Epoxy/HS) | 1700 | 1200 |
| MMC (6061 Al/SiC) | 2700 | 3000 |
| Acrylic | 1200 | 103 |
| PVC | 1400 | 48 |
| ABS | 1060 | 20 |

## 2.3 Navigation and Control

As the name suggests, AUVs must be able to operate in an autonomous manner. Therefore, a reasonably accurate navigation system embedded into it is essential for it to be able to acquire its current location at all times. (Leonard, Bennett, Smith, & Feder, 1998) In order to ensure that a good navigation is established, a reasonably good controller is required. A judicious design of the controller, however requires the mathematical model of the AUV which describes the kinematics as well as dynamics of the AUV of interest. A number of established models that have been developed, namely the Humphreys, Nahon and Fossen models (Fossen, 1994). Apart from deriving the model from first principle, obtaining the model via 'black box' or system identification approach by acquiring the output as well as the input signals of the AUV is also feasible in order to capture the complete behaviour of the model of interest.

In terms of control techniques, there has been a myriad development on control algorithms from simple to intelligent algorithms has been employed to improve the dynamic response of the AUVs. Wettergreen et al. has successfully implemented a simple PID tracking controller (Wettergreen, 2000) by extending the computed torque control often employed on robotics on an AUV. Nonetheless, it is worth to note that this type of controller requires reasonably accurate model in order to work well. Fuzzy logic based controllers have also been successfully demonstrated on AUVs (Kwiesielewicz, Piotrowski, & Sutton, 2001; Song & Smith, 2000). This type of controller in contrast of the former, does not necessarily require the exact modelling of the AUV. It reduces the need to mathematically model complex behaviours for instance hydrodynamic modelling, however the implementation of the controller itself is complex as the fuzzy inference as well as the membership functions must be appropriately acquired in order for it to work well. Other forms of advanced controllers that have been implemented are adaptive control (Fossen & Fjellstad, 1996) and sliding mode control (Healey & Lienard, 1993). Hybrid controllers such as neurofuzzy controller and sliding mode adaptive control (Filaretov, Dyda, & Lebedev, 1995). The unification of different types of control techniques are adapted to further improve the robustness as well as the fault tolerance of the hybrid controller.

There are three primary navigation methods namely dead-reckoning and inertial navigation systems, acoustic navigation as well as geophysical navigation techniques. The dead-reckoning method obtains the position of the vehicle by integrating the vehicle's velocity. However, velocity measurement may be affected by sea current, therefore, more often than not, inertial navigation is used as it is more accurate than velocity measurements. The position is obtained via integrating the acceleration measurement twice (Lee et al., 2007). GPS positioning may be used to correct accumulated position errors that arises from both methods (Leonard et al., 1998). Acoustic navigation on the other hand, utilises external transducers which return the acoustic signal send out by the vehicle. The travel time of the signal is used to determine the position of the vehicle, nonetheless, reflections and differences in the signal speed may influence the measurement. Geophysical navigation technique utilises the a priori knowledge of terrain to identify its current position. However, the reliability of the system depends on the exact knowledge of the map, which is not often readily available.

## 2.4 Propulsion, dive and buoyancy

Thrusters are often used as a propulsion mechanism as it provides a more accurate and faster response. Both horizontal and vertical movement of AUVs may be achieved by means of thrusters (Valavanis, Gracanin, Matijasevic, Kolluru, & Demetriou, 1997). The vehicle is able to move vertically as well as hover without propulsion as it has neutral buoyancy if thrusters are utilised (Serrani & Conte, 1999).

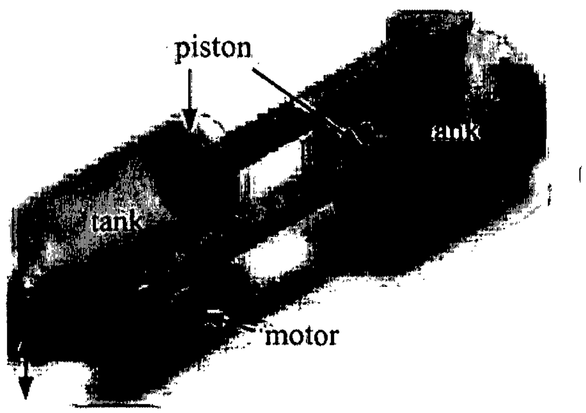


**Figure 3:** Static diving principle - Piston ballast system with two tanks
Source : (Wang, Engelaar, Chen, & Chase, 2006)

In terms of diving principles, it may be demarcated into static and dynamic (Wolf, 2003). The most common static diving method is the piston ballast tank. It consists of a cylinder and a piston. Its working principle is similar to of a large syringe pump. This setup is electrically easy to control as the pistons are moved by linear actuators which allows accurate depth control with straightforward programming. The hydraulic pumping system is another form of static diving method. It utilises an internal reservoir of hydraulic fluid and the actuation of the piston movement is driven by a pump to vary the AUVs buoyancy. Air compressor system also falls under the static category. It consists of a compressed air storage tank, a water tank and two normally closed valves which is used to vary the bouncy of the AUV. Conversely, direct thrust systems fall under the category of dynamic diving method. It utilises the vertically mounted thrusters to cause the AUV to dive.

## 2.5 Sensors and instrumentation

There are a number of sensors that are used in the navigation of AUVs. Pressure sensors are used to determine the external pressure exerted on as well as measuring the depth of the vehicle (Williams, Newman, Dissanayake, Rosenblatt, & Durrant-Whyte, 2000). The speed of the vehicle may be measured by means of a compass and water speed sensor. Doppler velocity logs (DVLs) may be used to measure the AUV's velocity with respect to the ground. The accuracy of the position estimation may be improved significantly through Kalman filtering (Lee et al., 2007). The DVL acquires the velocity by measuring the Doppler shift of sonar signals reflected by the ground. Nonetheless, this technique produces inaccurate results at low speeds. The inertial navigation system (INS) employs accelerometers as well as gyroscopic sensors to measure the acceleration of the AUVs (Stutters, Liu, Tiltman, & Brown, 2008). It is more accurate compared to velocity sensors as it is not influenced by sea currents.

## 2.6 Power supply

The most common power supply utilised in AUVs reported in the literature is batteries (Smith, James, & Keller, 1996). The simplicity, ease of speed control as well as silent operation made electrical-based propulsion more preferable as compared to thermal-based propulsion (Bradley, Feezor, Singh, & Sorrell, 2001). Most AUVs utilises rechargeable batteries, which are light to reduce vehicle weight. Lithium-polymer batteries are preferred as it has one of the highest energy density amongst other rechargeable batteries. Table 4 lists down the energy densities of batteries that have been utilised in AUVs.

**Table 4:** Battery characteristics (Bradley et al., 2001)

| Chemistry | Energy density (W.hr/kg) | Cycles | Comments |
|---|---|---|---|
| Alkaline | 140 | 1 | Inexpensive, easy to work with |
| Li Primary | 375 | 1 | Very high energy density |
| Lead Acid | 31.5 | ~100 | Well established, easy to work with |
| Ni Cad | 33 | ~100 | Very flat discharge curve |
| Ni Zn | 58.5 | ~500 | Emerging technology |
| Li Ion | 144 | ~500 | Complex circuitry |
| Silver Zn | 100 | ~30 | Can handle very high power spikes |
| Li Polymer | 265 | ~500 | Light and high energy density |

## 2.7 Concluding remarks

Several important criteria of AUV that have been reported in the literature were discussed in this chapter and they serve as a guideline for this project. A watertight electronics compartment that is a part of the hull of an existing AUV has to fulfil the minimum drag configuration to obtain maximum working range of AUV. Low drag coefficient may be achieved by using tear-drop shape, however, it does not offer the best volume for circuit storage. Therefore, the cylindrical hull design is selected as it is deemed to be the best alternative for low drag coefficient while maintaining the maximum storage volume as well as the ability to withstand strong pressure. In terms of material, ABS has the best strength to weight ratio compared to PVC, with regards to the present study as the desired depth considered is maximum 15 meters. In addition, ABS is non-corrosive. Owing to the off-the-shelf nature of PVC, it hinders the customisation of the compartment design feature. ABS, on the other hand, is capable to cater customisation through the use of 3D printer. Although the cost of ABS is expensive compared to PVC, nonetheless this type of material is much cheaper compared to metal-based materials and metal matrix composites.

In terms of mathematical modelling, although there are a few established models, they are not suitable for this project as the existing AUV does not comply to these models. A simplified model, which will be elaborated in the following section is deemed more suitable as it could appropriately describe the dynamics behaviour of the AUV of interest. Owing to the requirement of this research, the classical control architecture, namely the PID algorithm will be used in this study as the disturbances of water current is assumed to be negligible. Due to the cost constraint, the cheapest solution for navigation, which is the dead-reckoning and inertial navigation system is chosen. The error occurred in the inertial navigation system can be compensated by the use of GPS module, whereby the GPS coordinates of the AUV is updated every time when it surfaces.

In fulfilment of the size requirement of AUV, the dynamic diving principle is chosen over static diving principle as it requires less volume as the static diving principle. Furthermore, the thruster-based dynamic diving principle allows variable buoyancy. Owing to the high current demand nature of thrusters, high density battery is required on-board to sustain the power required for a given mission. Therefore, Lithium Polymer (LiPo) batteries are chosen to achieve the power requirement of the AUV and subsequently reduce the weight of the AUV assembly. As a result, power consumption can be significantly reduced as the power consumption increases with the weight of AUV.

# CHAPTER 3

# METHODOLOGY

## 3.1 Introduction

This chapter discuss the four main project phases which are development of electronics circuit for the micro AUV, development of watertight electronics compartment for micro AUV, simulation of position control of micro AUV using Proportional–Integral–Derivative (PID) controller and the controller development for micro AUV. The flow chart of project methodology will also be discussed in this chapter to showcase the overall project flow.

## 3.2 Flowchart of Project Methodology

First of all, literature reviews were carried out to get better understanding of AUV in terms of its structure, control and navigation, sensors and power supply. An interview was carried out with Assoc. Prof. Dr. Shahbudin at International Islamic University Malaysia to get the insights of coral reef monitoring project and the need of AUV in the aforementioned project. Existing AUV structure was then modelled in Autodesk Inventor 2016. Electronics circuit and watertight electronics compartment were designed concurrently to suit the existing AUV without any necessary modification. The design was analysed with the built-in stress analysis in Autodesk Inventor check the structural integrity of the compartment. A simplified model of AUV based on the existing AUV was derived and position control of the AUV with PID controller was simulated in Matlab. At the same time, the watertight electronics compartment and electronics circuit were fabricated and assembled to the existing AUV. Microcontroller was further developed to control the AUV through tethered cable for future system identification test.