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Development of ROV based Water Tank Cleaning Robot

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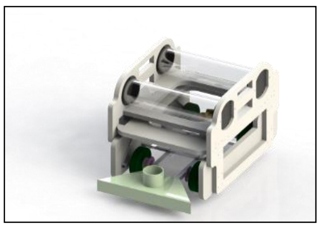
Graphical abstract



Abstract

Clean water supply is important in ensuring good health of people. Water supply is distributed from water storage tanks. Sediment that accumulates over time in water storage tanks will deteriorate the water quality used by consumers. Therefore, water storage tanks are required to be cleaned once in every three years by water utility operators or tank cleaning service providers. Manual cleaning method is done by draining off and resupply water into the tank after workers have cleaned the tank using water jet and brushes. In this paper, an alternative cleaning method using a Remotely Operated Underwater Vehicle (ROV) is proposed. Using ROV, water supply disruption can be prevented and cleaning process will be more efficient and cost effective. An ROV is built to operate underwater and vacuum out sediments from water tank. Operator on screen can see live-streaming video. Raspberry Pi is used as the main communication board to interface with MATLAB. Operator will operates the ROV remotely to carry out the cleaning process. IMU sensor was also used for simulation study in MATLAB for orientation movements testing.

Keywords: MATLAB; raspberry Pi; ROV; underwater; water tank cleaning

1.0 INTRODUCTION

In water storage facilities, the maintenance of water quality involves the cleaning of floor and walls of water tank that stores the water [1]. All water tanks accumulate sediment over time. One particle at a time, from a half to three inches is a common amount of build up over several years. Sediment that gathers on the bottom of the tank floor is seldom thought about. The water is often tested daily, if the chlorine residual goes down, operators do not ask why and they just add more chlorine. After a long time, the additional chlorine breaks down and becomes contaminate in the tank that can cause cancer [2]. Instead of constantly adding more treatment chemicals, cleaning sediment from the floor of tanks is a better solution.

Water storage tank or service reservoir (SR) was cleaned using manual cleaning method. Sediments were collected with a high-pressure vacuum pump, and either move them to a reprocessing facility or incinerate them. This manual method could take up to several months, expensive, and water utility had to close down operation, unable to provide water during the cleaning period [1]. Also, removal of sediment deposits manually by dredging or excavation is a costly operation, which may be justified by the economic value of the water, and the need of replacing lost reservoir capacity [3]. Additionally, the draining of water tank could cause stress cracks and possible leaks from water main. A big amount of consumer complaints received by SYABAS in 2004 regarding frequent water disruptions and low water pressure can be seen in Table 1 below due to manual cleaning of water tanks [4].

In the recent years, underwater cleaning robots are devices that were developed in order to resolve the problems in traditional method of manual cleaning by making it possible to carry out underwater cleaning of sediments [1] which is also called as online cleaning.

Table 1 Consumer complaints in 2004

No.	Type Of Complaint	No. Of Complaints			Total
		Jan - Mar	April	May	
1	Pipe Burst	1,938	776	766	3,480
2	Pipe Leak	13,843	5,781	5,923	25,547
3	Low Pressure	1,048	515	473	2,036
4	Dirty Water	444	160	274	878
5	Odour	78	31	1	110
6	No Water	2,424	1,086	1,280	4,790
7	High Bill	2,124	1,374	1,362	4,860
8	No Water Bill	97	34	17	148
9	Meter Lost/Stolen	265	124	96	485
10	Pilferage/Illegal Connection	262	145	215	622
	TOTAL:	22,523	10,026	10,407	42,956

Underwater cleaning robot is the combination of underwater vehicle namely, Remotely Operated Underwater Vehicle (ROV) with cleaning function. The type of ROV focus in this project will be the special use ROV as shown in Fig 1. The special use ROV has non-swimming nature such as crawling underwater vehicles, towed vehicles, or structurally compliant vehicles [5]. A ROV is a tethered (a group of cables that carry electrical power, video and data signals back and forth between the operator and the vehicle) underwater robot [6], powered by a propulsion system and controlled by a control board or computer. ROVs are normally deployed for dangerous underwater tasks, for example the search & rescue operation, underwater surveying, inspection, repair and maintenance [7].

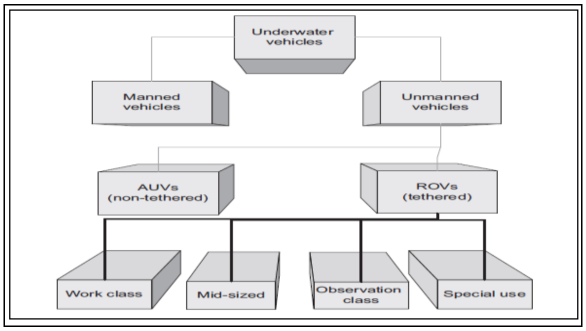
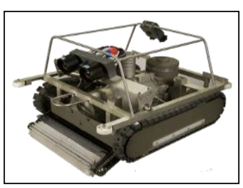
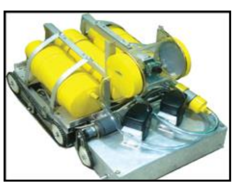


Figure 1 Underwater vehicles and ROVs

ROV for domestic and industrials tank cleaning has been developed abroad and in Malaysia but not vastly as compared to tank inspection ROVs. Different types of reservoir structures and water management methods are being used according to the procedures implemented by corporations and water utility. Therefore, specialized ROVs are often developed specifically for certain types, size and condition of reservoirs [1]. There are several robot developed as shown in Figure 2 such as VR600 by WEDA (Sweden), SaUsR robot by Gridbots (India), PIRO-U3 by Pohang Institute of Intelligent Robotics (Korea), SCANTRON SR24 by Scantron Robotics Inc., CS-600 robot by Nex Generation Solutions and lastly Robotic cleaner by WQ Enterprise (Johor).


WEDA's VR600


Gridbots' SaUsR

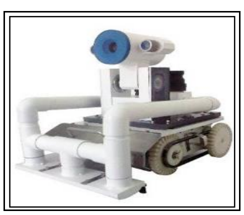

WQ Enterprise robotic cleaner

Figure 2 ROVs for underwater tank cleaning

The most notable features of WEDA is that it is equipped with a built-in submersible camera and light which enable operators to visually confirm underwater conditions while working, and has an all-in-one driving & pumping system. Gridbots' SaUsR robot uses a simple cleaning and suction mechanism. Once SaUsR reaches the bottom of the tank, the counter suction unit starts operating. The two brushes in the suction unit will scrubs the sludge off and creates a whirlpool of water and the sludge. Then, the pumping unit will sucks out the mixture of water and sludge. Besides that, the operator can choose between two pumping mechanisms. The first pumping unit will sucks out the contaminated water and disposes it using an outlet hose. The second pumping unit has a filter attached to the robot to separates the sludge deposit from the contaminated mixture while it is still under the cavity [8]. Lastly, WQ Enterprise plastic robot was hooked up to a vertically suspended hose, which would channel dirt and sediments out of the reservoir. Plastic was used as robot body material to prevent bacteria or rust from polluting the water. For eight hours a day, operators will control using joystick and monitor the cleaning process via a screen synced to the built-in camera on the robot [9].

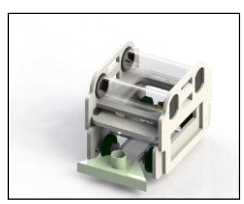
This project consists of four main parts, which are ROV hardware design development, electronic system development, communication system development and ROV cleaning mechanism. A ROV prototype that can vacuum out small amount of bottom sediment, provide live-streaming video and data feedback to operator has been developed. Testing of ROV functionality underwater in a small water tank with depth of 1 meter had also been carried out.

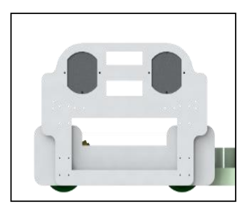
■2.0 ROV SYSTEM DESIGN

In the development of this ROV, Solidworks 2013 software was used in designing the ROV structure. After designing, the ROV was built.

The ROV design can be divided in four main parts, which are main body, electronic tube for circuit housing, base and suction head. The Solidworks dimension of the ROV is 70 cm (l) x 42.5 cm (h) x 44 cm (w). The Solidworks rendered images of ROV can be seen in Figure 3. From Figure 3(a), it can be seen that both side of the ROV main body structures are having the same type of symmetrical shapes. Besides, there are two electronic cylindrical tubes separated symmetrically as well to allow for more stable, centralized buoyancy and center of mass [10]. Additionally, the two separated electronic tubes allow for easy replacement and upgradeability of certain electronic components.

The ROV separate parts design can be seen in Figure 4 which consist of suction header, electronic tube and base. The suction head was designed in such a way that it has a wider and confined suction area and at the same time prevent water to be stirred vigorously when the suction pump is turned on to suck up the sediment. Wheeled base in Figure 4(c) was chosen over combat tank tracks type, as the propulsion system is much simpler by using wheels, axle and bearing mechanism. Combat tank tracks will also tend to get loose or wear out over time.


(a) Front view


(b) Side view

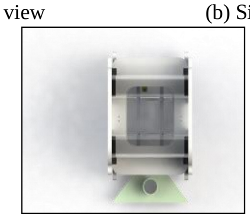
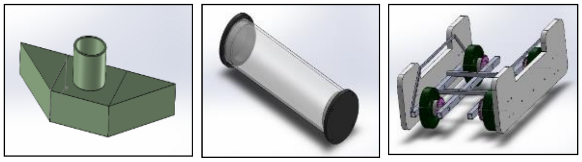


Figure 3 Solidworks rendered images of ROV



(a) Suction head (b) Electronic tube (c) Base

Figure 4 ROV separate parts

Besides the Solidworks 3D CAD drawing, the structural analysis of the ROV has been carried out. The structural analysis is to determine the maximum pressure which the electronic tube can withstand when undergo underwater mission. The analysis is shown in the Figure 5 below. The electronic tube can go as deep as approximately 160 meters with a factor of safety of 1.54, which is sufficient in this project.

Center of gravity and center of buoyancy of the ROV also play an important role for an underwater vehicle. It will decide the stability of the ROV for its underwater movement. If the ROV has the robot will tend to become upside-down to achieve the stable state. The center of gravity and center of buoyancy properties can be determined with the CAD drawing. In Figure 6, it shows that the center of buoyancy is directly on top of the center of gravity. Hence, the design is consider stable under water. The further the distance between each two points, the better the stability but in the other will result in poor maneuverability.

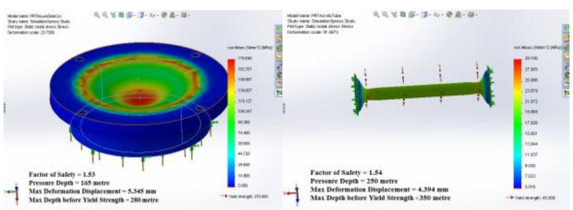


Figure 5 Structural analysis of electronic tube

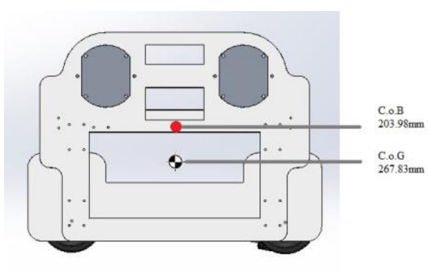


Figure 6 ROV center of buoyancy (C.o.B) and center of gravity (C.o.G)

The actual design of ROV is shown in Fig. 7. The actual ROV weight is approximately 27.9 kg. All the materials used for this project were commercial off-the-shelf components (COTS) and was obtained from local hardware, electrical and electronic shops.

Polypropylene plastic was chosen as the material for main body due to its likeliness with water in its density. Most of the parts in the design used anti-rust material such as aluminium, stainless steel, zinc and plastic. Steel was sprayed with a layer of paint to prevent it from rusting. Connecting bolts and nuts were also the stainless steel type. Suction head was made of zinc plate. Aluminium block was lathed/cut into specific shape using a type of machine tool to fit into the acrylic electronic tube used as electronic circuit casing. Black O-rings were used to seal the tube to ensure the tube is airtight. The aluminium plates were lined with O-rings and were clamped against the tube using screws, thereby providing waterproofing.

The ROV base was attached with power window motor to allow movement underwater. Power window motor is usually used in automobile side window actuation. It was selected as the ROV base actuator because it has thin rubber layer which separate the motor rotor from water. The ROV wheels in Fig. 7 consist of polyurethane material, also known as PU in short. It has lending characteristics such as durability and resistance to abrasion. Most importantly, it does not expand when submerged into water for a long time unlike rubber.

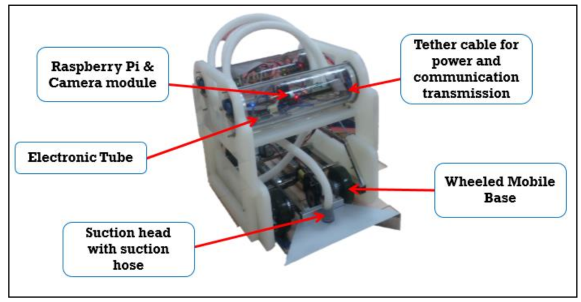


Figure 7 Actual design of ROV developed

The electronic system development for ROV is an important step in ensuring that ROV is able to function underwater with given power supply. The overall ROV system was designed in such a way that it is simple and comprehensive enough to provide the required ROV functions. Furthermore, the ROV system is a combination of hardware and software interface, which makes it an integrated system.

The ROV consists of three main electronic components, which are Raspberry Pi Model B single-board computer, STM32F3 Discovery microcontroller and dual channel 10A DC Motor Driver as shown in Figure 8.

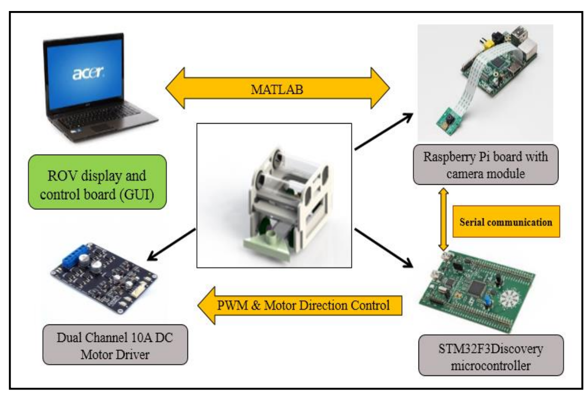


Figure 8 ROV overall system

Raspberry Pi is a credit-card sized single-board computer with 8GB SD card used for booting and long-term storage of information such as operating system, programs and the data needed to run the Raspberry Pi. Raspberry Pi board is used as the main communication board to interface with MATLAB software using the Raspberry Pi MATLAB support package installed. The MALTAB version used in this project is MATLAB 2014a version, which provides MATLAB support package for

Raspberry Pi where it has the feature to do MATLAB programming interface with Raspberry Pi hardware.

Raspberry Pi board was chosen because Raspberry Pi Camera Board and serial port features in MALTAB can be used as the main programming channel to provide live-streaming video and serial connection to STM32F3 Discovery Microcontroller to control the motors. Additionally, Raspberry Pi price is reasonable and easy to obtain in case of replacement. Only one dual channel motor driver was used to control the two power window motors.

The overall circuit connection, which includes the flow of power supply, can be seen in Figure 9. ROV tether system consists of 15 m power cord and 15 m LAN cable. The LAN cable is used for communication between MATLAB, Raspberry Pi board and STM microcontroller. The power cord is connected with a 12 V Li-Po rechargeable battery as power supply to ROV.

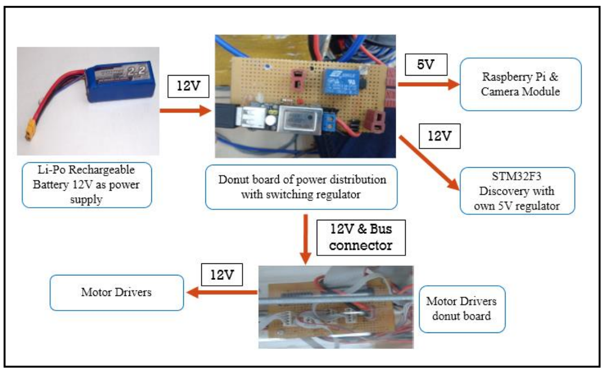


Figure 9 Overall circuit connection diagram

A Raspberry Pi Camera Module was used to provide underwater vision instead of webcam because of its compatibility with MALTAB 2014a support package. The camera module features 5 megapixels of still image capture and up to 1080p of full high definition of video recording

ROV Graphical User Interface (GUI) was developed in this project to serve as ROV Display and Control Board. The ROV GUI was developed through MATLAB 2014a software using GUIDE interactive tool. GUIDE (GUI development environment) provides tools for designing user interfaces for custom application.

Figure 10 ROV GUI

This project ROV GUI as shown in Figure 10 consist of several functions such as live-streaming video display from Raspberry Pi camera module, image capture function to capture underwater images from camera, control buttons to control the ROV and lastly speed slider function to control the motor speed. The ROV GUI will be seen in normal laptop and the control buttons for motors can be activated using either mouse clicking or keyboard press feature. The rest of the capture image button and speed slider function will be using mouse clicks. Additionally, the image captured will be saved in the MATLAB Workspace and can be extracted out into image file format .png to be view later by user.

The ROV cleaning mechanism was based on simple suction method of sediment. The inlet suction hose attached at ROV suction head will be connected to inlet of water pump and then the sediment will be drained out from water pump outlet once the pump is turned on. The set-up of ROV cleaning mechanism is shown in Figure 11 below. The water pump purchased is a centrifugal pump where it has an impeller near the inlet part of water pump where fluids entered. The impeller will rotate when the water pump electric motor is turned on and thus the fluids will flowed radially outward to the water pump outlet. The flow rate of this pump is 110 l/min and maximum suction height is 32 m.

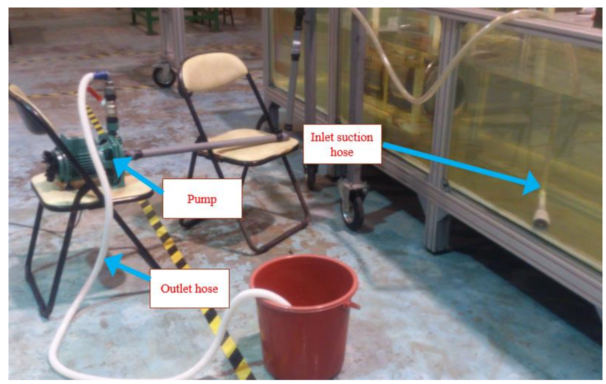


Figure 11 Cleaning set-up

■3.0 DEVELOPMENT OF INTERTIAL MEASUREMENT UNIT (IMU) SENSOR

IMU consists of several sensors like accelerometers, gyroscopes and magnetometers. These sensors are combined together to measure velocity, orientation and gravitational of a body referred to earth's frame. Accelerometer measures acceleration of a body including the gravitational acceleration. Gyroscope is used to measure body's rotational or angular velocity and magnetometer measures the strength of earth's magnetic field. By making full use of these measurements, orientation of a body in Euler's angles (roll, pitch and yaw) can be obtained. Orientation angles are useful in determining the heading of a body and also as feedbacks for stabilization. In this project, microcontroller STM32F3-Discovery by STMicroelectronics are used because it has 9 DOF sensors (triaxial accelerometers, triaxial gyroscopes, and triaxial magnetometers).

Accelerometers and magnetometers were calibrated first before applying method by Madgwick *et al.* [11] to obtain orientation. Gyroscope correction is done in real time thus no pre calibration is needed. Accelerometers are tuned in such the way that offset measurements are compensated and multiplied with a scale factor to make sure the maximum and minimum readings of the triaxial accelerometers are the same. Besides that, a skew matrix is applied in the factor matrix to remove the non-orthogonality existed. The mathematical model to obtain the output of triaxial accelerometers can be described as

The matrix S is scale factor, O is the offset, V is raw

$$A = S(V - O)$$
$$where,$$
$$S = \begin{bmatrix} 0.9560 & -0.0016 & -0.0023 \\ -0.0016 & 0.9541 & -0.0012 \\ -0.0023 & -0.0012 & 0.9448 \end{bmatrix} \quad (1)$$
$$O = \begin{bmatrix} -0.0801 \\ -0.0635 \\ -0.3473 \end{bmatrix}$$

Accelerometer value and A is the output. The effect of calibrated accelerometers can be seen referring to Figure 12.

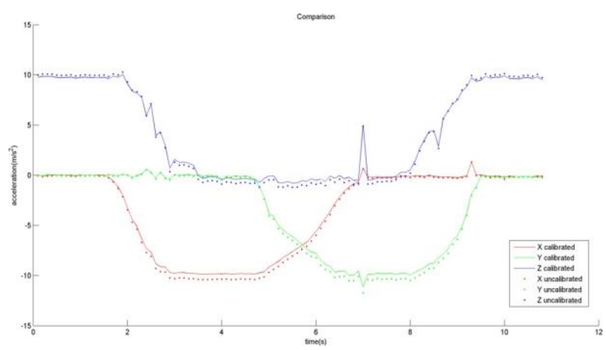


Figure 12 Comparison between raw and calibrated values

Magnetometers are prone to two types of disturbances, which are hard, and soft iron effect. Hard iron disturbance is caused by permanent magnets fixed near to the sensors while soft iron disturbance is caused by earth magnetic interference with magnetically soft material surround it. An available ready use source to calibrate magnetometer is developed by Davide Gironi [12]. The author uses Matlab to tune the sensors. This method uses raw data from magnetometers to visualize an ellipse and is fitted into a sphere by multiplying the raw data with a scale factor. The mathematical model of the described method is,

$$Y = S(M - O)$$
$$where,$$
$$S = \begin{bmatrix} 0.9051 & -0.0029 & 0.0113 \\ -0.0029 & 0.9280 & 0.0045 \\ 0..0113 & 0.0045 & 0.9983 \end{bmatrix} \quad (2)$$
$$O = \begin{bmatrix} 0.0526 \\ -0.125 \\ 0.0375 \end{bmatrix}$$

where S is the scale factor, O is the offset, M is the raw data and Y is the output data. The Figure 13 and Figure 14 show the result between calibrated and uncalibrated data.

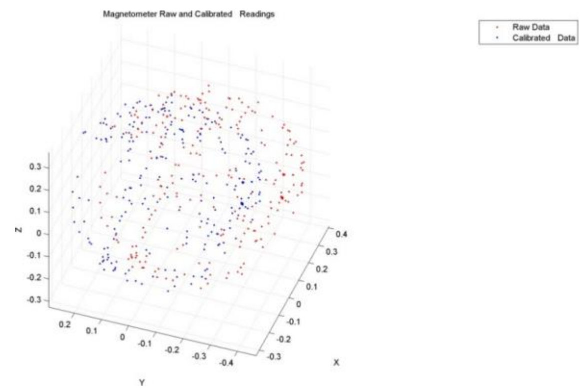


Figure 13 Raw data against calibrated data plotted in three axes

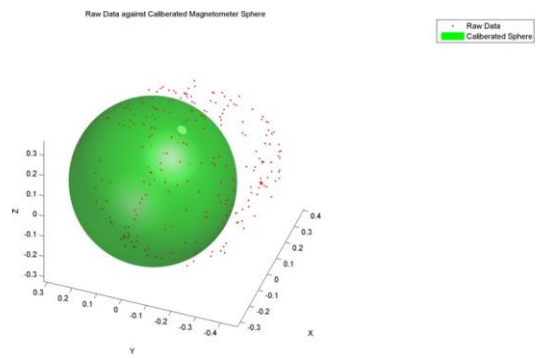


Figure 14 Comparison between calibrated data in green sphere against raw data

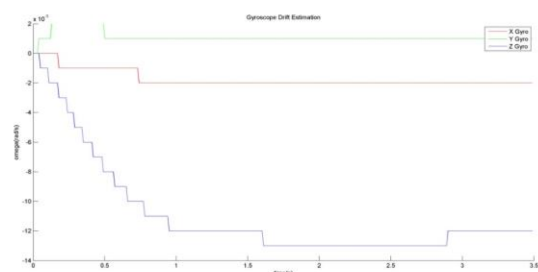


Figure 15 Convergence of gyroscope drift estimation

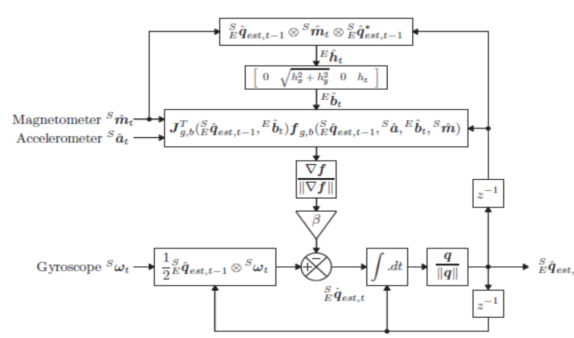


Figure 16 Block diagram representing method developed by author

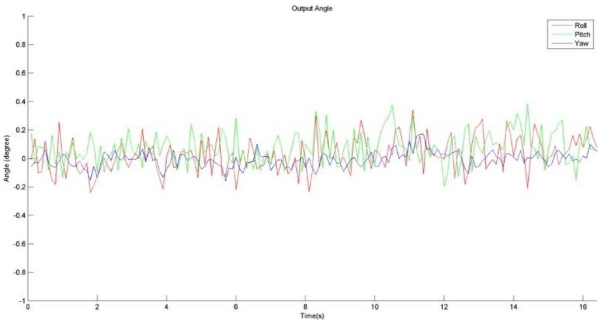


Figure 17 Output for none rotation applied

The method by Sebastian OH Madgwick [11] uses gradient descent algorithm to compute the orientation of IMU. There were two internal corrections to compensate the integral drift error, which were gyro drift error correction, and non-orthogonality correction. Quaternion angles were used in this algorithm to prevent singularity. Two variable gains were used, $\beta = 2.0$ for non-orthogonality and $\zeta = 0.01$ for gyroscope drift correction. As this method is recursive and able to correct gyroscope drift, gyroscope drift rate is estimated and the convergence rate can be seen in Figure 15. Overall, this method can be summarized as in Figure 16. Figures 17 and 18 show the output angles for still orientation and series of rotations.

A graphical user interface (GUI) is developed to validate the result of estimated orientation by observation. Matlab software is used to interpret data from microcontroller and rotate a 3D object in .wrl format accordingly, which is later shown in Figure 19.

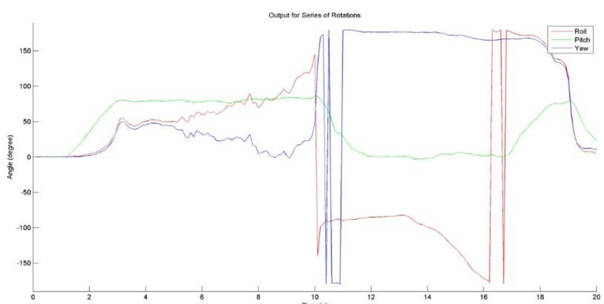


Figure 18 Output for series of rotations applied

■4.0 RESULTS AND DISCUSSION

ROV underwater testing inside a water tank was carried out to evaluate the ROV navigation and cleaning functionality. The ROV GUI system had been tested and the effectiveness of the GUI system will be discussed. The ROV and cleaning mechanism was set-up as shown in Figure 20. The testing was done in a water tank with dimension of 1m (l) x 1m (w) x 1m (h). Therefore, the expected depth of water tank for this project which is 1m was chosen for the ROV testing. All the suction hose, water pump, and laptop with MALTAB GUI were connected during the set-up before the ROV was put into the water.

The ROV navigation was tested in the water tank before the actual cleaning process of ROV will be done. This test is to ensure that the ROV will be able to navigate underwater effectively by receiving command from GUI control panel in laptop. ROV forward-backward movement and overall turning movements were tested and both results can be seen in Figure 22 and Figure 23 respectively. The ROV waterproofed capability was tested by submerging the ROV inside the water tank and power was supplied to the ROV. The images shown in Figure 21 were taken externally with hand phone which showed that the ROV is powered up and the LED of certain electronic components like camera, motor drivers and STM were seen turned on.

The small images in the right bottom corner of the images shown in both Figure 22 and Figure 23 were taken directly from Raspberry Pi camera when the camera is turned on underwater. The experimental results of overall ROV turning movements from right to left direction during underwater can be seen from left to right starting from the first image until the last image in Figure 23. From the results, it can be verified that the ROV control and communication system is functioning well underwater without any sudden breakdown when movement is done continuously.

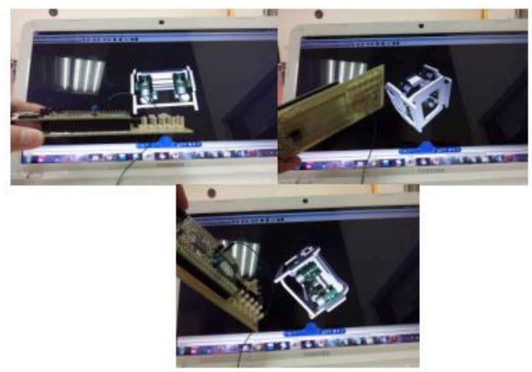


Figure 19 Actual Simulation of ROV movement with IMU

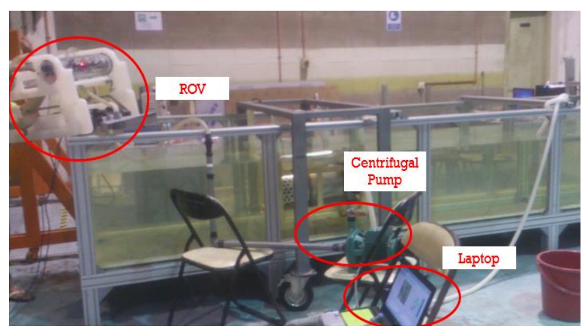


Figure 20 ROV underwater testing set-up

Figure 21 ROV submerged inside water

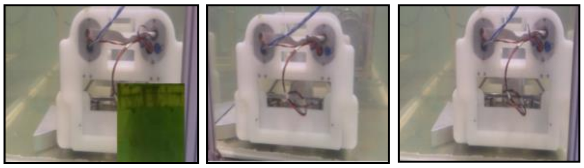


Figure 22 Experimental results of forward-backward movements

The last stage of testing was carried out to test the ROV cleaning capability. The ROV was controlled to clean up specific area in the water tank where the small amount of sediment was located as shown in Figure 24. The type of sediment used is normal dry soil.

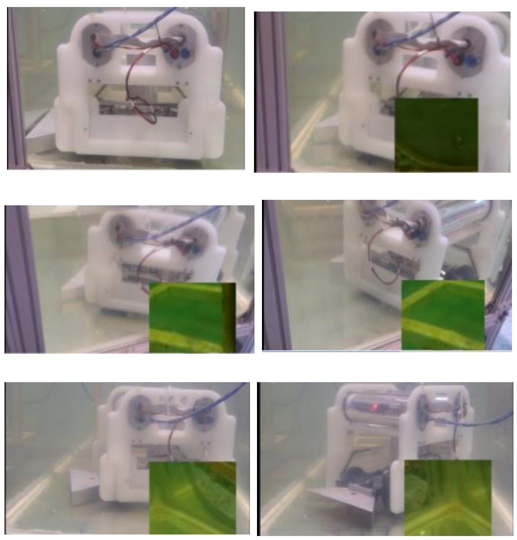
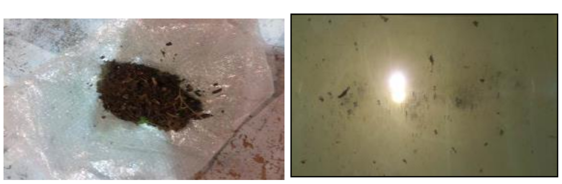


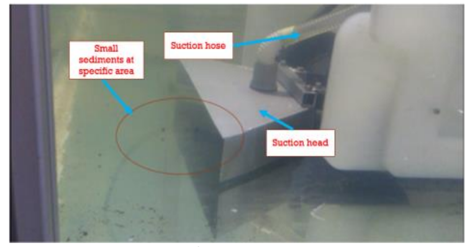
Figure 23 Experimental results of overall ROV turning movements

Figure 25 shows small amount of sediment at the red-circled area in front of the suction head before cleaning and also the outcome after ROV cleaning. From the experimental results obtained, it can be verified that the ROV suction hose and water pump was able to suck out the small sediments from the water tank's floor.

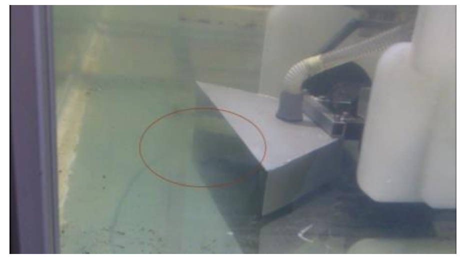


Normal dry soil Small sediment in tank

Figure 24 Type of soil and sediment in water tank



Before cleaning



After cleaning

Figure 25 ROV cleaning result

■5.0 CONCLUSION

ROVs development has been an on-going research and development area. Several university students, researchers and even companies are constantly improving current ROVs system that can be suitable to use in various tank-cleaning applications. In this project, the ROV prototype developed has a simple open body structure, which is detachable and consisted of electronics components which are easy to obtained and replaceable with other components for additional ROV functions. Besides, the ROV GUI system developed act as display and control board of ROV to replace remote control and monitor. Operator using just a laptop can control the ROV remotely.

This project manage to obtained result where the ROV is able to suck out small amount of sediment from water tank with tank depth of 1 m. Lastly, future work on testing with bigger and thicker amount of sediment in real water tank can be done to further validate the ROV cleaning effectiveness. In the same time, the IMU sensor feedback is also very useful to provide the ROV orientation for a better controlling experience and can be even further improved into an autonomous underwater vehicle.

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