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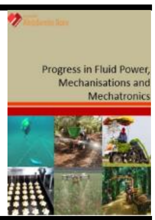

Lessons learned from UTeM Autonomous Underwater Vehicle Competition Initiatives

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ABSTRACT

This paper describes the development and lesson learned from the participation of UTeM Underwater Research Group (UTeRG) in three autonomous underwater vehicle (AUV) competitions. In 2017, a team from Universiti Teknikal Malaysia Melaka's responded to a challenge in an autonomous underwater vehicles competition organized by the IEEE Oceanic Engineering Society (OES), which was held in Malaysia and Singapore. The international competition gives participants the opportunity to experience the engineering trials and develop skills in autonomous underwater vehicle (AUV) technology. The research team has developed 4 prototypes of AUV, known as TUAH 1.0, TUAH 2.0, PANTHER and PANTHER-J. This paper describes the development of each AUV, the specifications, the data and lesson learned during each competition. The team has been supported by the Malaysian Chapter of IEEE Oceanic Engineering Society (OES) and IEEE Robotics and Automation Society (RAS), and Universiti Teknikal Malaysia Melaka.

1. Introduction to Autonomous Underwater Vehicle Competition all over the world

An autonomous underwater vehicle (AUV) is a robot that travels without requiring input from an operator. It relies on multiple sensors, controllers, propulsion system and power management to navigate autonomously deep into the ocean [1]. By the end of 20th century, international competitions on AUV began to emerge, as shown in Table 1. In the United States of America, Robosub emerges as the first international AUV competition that is initiated by the Association for Unmanned Vehicle Systems International (AUVSI) 1998 [2-3]. Co-sponsored by Office of Naval Research, the Robosub competition is now a widely contested competition with various participation by international student each year. The AUVSI also initiated the international SeaPerch and Roboboat

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challenge, which is the competition for remotely operated underwater vehicle (ROV) and autonomous surface vessel (ASV). In Europe, autonomous vehicle competition was initiated in 2006 by the name of the Student Autonomous Underwater Vehicle Challenge, Europe, which is also known as SAUC-E. [4]. Co-sponsored by NATO Centre for Maritime Research and Experimentation (CMRE), the competition was held annually across Europe, between United Kingdom, France, Croatia and Italy from 2006 to 2018 respectively. In the Asia region, the National Institution of Ocean Technology of India, (NIOT), with the collaboration of the IEEE Oceanographic Engineering Society (OES) India Chapter and Ocean Society of India started a national level AUV competition, known as the Student Autonomous Underwater Vehicle, SAVe, in 2011 [5]. The national competition is opened to students from various parts of India [6]. To the north of Asia, the Oceanology International China Underwater Robot Competition was firstly held in Shanghai, China in 2013. Being fully sponsored by Oceanology International (OI), the competition connects the international marine technology and ocean science communities with the local market.

Fig. 1. Participants of the Singapore Autonomous Underwater Vehicle Competition (SAUVC2017).

Table 1
Autonomous Underwater Vehicle Competition around the Globe

Start Date	Country/Region	Competition
1998	USA	Robosub
2006	Europe	Student Autonomous Underwater Vehicle Challenge, Europe (SAUV-E)
2011	India	Student Autonomous Underwater Vehicle (SAVe)
2013	China	Oceanology International China Underwater Robot Competition
2013	Singapore	Singapore Autonomous Underwater Vehicle Challenge (SAUVC)
2016	Japan	Underwater Robotic Convention
2017	Malaysia	Malaysia Autonomous Underwater Vehicle Challenge (MAUVC)

In 2017, Oceanology International China Underwater Robot Competition kicked off in the National Ocean Technology Center, Tianjin, with a theme of "Innovative Underwater Robot". The competition has attracted 45 teams from 19 colleges and universities nationwide. [7]. In Japan, the IEEE OES Japan Chapter had also organized their own Autonomous Underwater Vehicle in 2016. Also known as Underwater Robotic Convention, the annually held competition is conducted with the collaboration of Japan Agency for Marine-Earth Science Technology (JAMSTEC) [8]. In South East Asia, the IEEE OES Singapore Chapter started the Singapore AUV Challenge in 2013, as shown in Fig. 1, with aim to expose students to the engineering challenges of AUV design and also to develop an appreciation for the AUV related technologies. Meanwhile their neighboring country Malaysia, started their own Malaysia AUV Challenge in 2017 with collaboration from IEEE OES Malaysia Chapter and respective academic institutions [9]-[10]. This paper presents the preparation and the development of UTeM Underwater Research Group (UTeRG) in participated autonomous underwater vehicle competitions for two consecutive years. Lessons learned from all competition are explained in the last section of the paper.

2. Participation in Malaysia and Singapore Autonomous Underwater Vehicle Competition

In 2017, a team from Universiti Teknikal Malaysia Melaka's responded to a challenge in an autonomous underwater vehicles competition held in Singapore Polytechnic. The Singapore Autonomous Underwater Vehicle Challenge, dubbed as SAUVC, is an effort by the local chapter of IEEE OES to engage the international participants to the arduous challenges of AUV's design. The competition gives the opportunity for researchers and students from UTeRG to experience and develop skills in autonomous underwater vehicle (AUV) technology in the competition. The UTERG team also sends three AUV to Malaysia AUV Challenge 2017, namely UTeM 2.0, PANTHER and PANTHER-J. All AUV focuses on building the AUV from modified ROV platform, which is originated from BlueROV, BlueROV2 and OpenROV platform. The AUV team competed in both the Malaysian and Singapore Autonomous Underwater Vehicle Challenge in 2017 and 2018, respectively [11].

3. Technical Preparation

3.1 TUAH 1.0 AUV

Figure 2 shows the TUAH 1.0 AUV during a competition. The design for the AUV involves independent autonomous navigation using a programming that is written and downloaded into microcontroller Arduino MEGA, which is responsible for both relaying motor commands to individual thrusters. The programming is developed by using Arduino integrated development environment (IDE) programing software, where a wiring-based language is used. Arduino code is based on the Java and C++ libraries, with an open source software tool that can sense, monitor, store and control algorithm provided to the microcontroller. The sensors are equipped with MPX5700AP depth sensor for vertical movement control and inertia measurement unit (IMU) for yaw, roll and pitch measurement. Table 2 shows the TUAH 1.0 AUV specification used in the event.

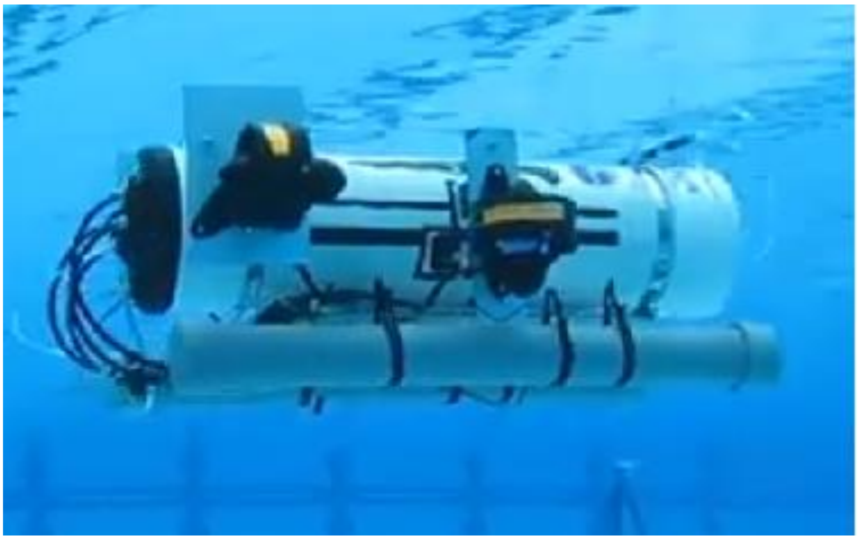

Fig. 2. TUAH 1.0 AUV in action

TUAH 1.0 AUV is powered by a 12V battery and located in the waterproof polyvinyl chloride (PVC) hull. while acrylic was used in the frame, for weight reduction and corrosion resistance. Four skid rods are used in between the frames to improve stiffness. Pixy (CMUcam5) camera for target recognition and the thrusters are used for forward, reverse, upward and downward movement. The camera is mounted on a separated water-proof casing, on the top front of the AUV to provide a forward and downward view for navigation and object recognition [12].

Table 2
TUAH 1.0 AUV specification

Name	TUAH 1.0
Dimension	70cm x 50cm x 30cm
Weight	18kg
Speed	0.4 m/s (25% of full speed)
Depth	3 to 5 meters
Hull	Polyvinyl chloride (PVC)
Frame	Poly(methyl methacrylate) (Acrylic)
Thrusters	4 thrusters T-200
ESCs	Afro ESC 30A
Controller	Arduino MEGA.
CPU	ATmega2560
Batteries	1 Yuasa 12V 8Ah, 1 9V battery
Sensors	**10 DOF IMU, MPX5700AP** Depth Sensor
Switch	On/Off
Tether	None
Ballast	70mm pebbles/cobble stones
Camera	Pixy Camera

3.2 TUAH 2.0 AUV

The TUAH 2.0 AUV is a new AUV designed for the competition. Figure 3 and Figure 4 show the design and actual setup of the AUV. The TUAH 2.0 AUV uses four T200 thrusters to provide four degree-of-freedom movement so that it can navigate independently of participants' intervention. The four thrusters installed on the AUV are each connected to their own pin on the Arduino microcontroller. All thrusters, linked to ESC, are capable of forward and backward thrust at various speeds. The speeds of the motors are set in between 0 to 255. The microcontroller produces pulse-width-modulated (PWM) waveforms as input signals to the ESC. The voltage levels of this signal vary in time between the common voltage and the microcontroller input voltage. The PWM signal consists of square pulses separated in time where the width of the pulse corresponds to the commanded position of a servo. A short pulse would drive a servo to its minimum range and a long pulse to the maximum range. The signal would signify low throttle (or no throttle) and long pulse to high throttle.

Fig. 3. TUAH 2.0 AUV

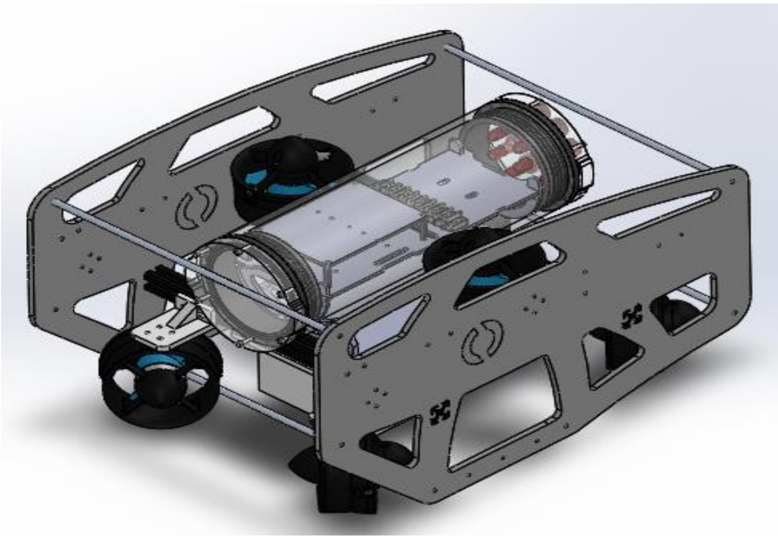

Fig. 4. Design cad of TUAH 2.0 AUV

The use of throttle here is related to the original use of a servo to literally close and open an air fuel mixture carburetor on a gas engine. For brushless motors, low throttle is used for low RPMs and high throttle for high RPMs. The Arduino microcontroller communicates with the camera for target recognition by utilizing open source programming that can be easily obtained from the internet. It can easily be connected through SPI, USB, I2C or UART for interfaces. **Table 3** shows the specification of TUAH 2.0.

Table 3
TUAH 2.0 AUV specification

Name	TUAH 2.0
Dimension	50cm x 50cm x 25cm
Weight	10kg
Speed	0.4 m/s (25% of full speed)
Depth	3 to 5 meters
Hull	Poly(methyl methacrylate) (Acrylic)
Frame	Poly(methyl methacrylate) (Acrylic)
Thrusters	6 thrusters T-200
ESCs	Afro ESC 30A
Controller	Arduino UNO
CPU	8 bit Atmel AVR
Batteries	1 9V Energizer battery 1 12V Lead-acid battery.
Sensors	10 DOF IMU
	MPX5700AP Depth Sensor
Switch	On/Off
Tether	None
Ballast	Coated Lead

3.3 PANTHER AUV

Figure 5 shows the PANTHER AUV, which is a modified version of unassembled BlueROV2 kit with ballast, frame, watertight enclosure, T200 thrusters and speed controllers [13]. The team opted in using Arduino UNO as the single board controller on the PANTHER AUV, instead of using the integrated Pixhawk-Raspberry Pi controller, originally designed for BlueROV2 remote controlled system. The reason of using Arduino UNO is that it consumes less power than Raspberry Pi and can be linked to different external devices. An Arduino board is best used for simple repetitive tasks, such as diving and resurfacing or swimming left and right during the competition. Arduino can also work with a wide range of input voltages. This allows it to run from a variety of different types of batteries and keep working as the battery reduces its power. The vehicle is powered by 14.8 V lithium-ion batteries. All the Arduino code is written in C++ using the Arduino libraries.

The battery voltage of the AUV is monitored through a special programming written using Arduino C++ codes. Analog signals from the battery monitor are converted into digital form by a 16-bit A/D converter. Onboard the main enclosure, inertia measurement unit or IMU measures and reports a body's specific force and angular rate, by using a combination of two-axis accelerometers and single-axis gyroscopes. The Arduino microcontroller, is used for relaying motor commands to individual thrusters and collecting sensor data back to the controller. There are 6 thrusters used for forward, reverse, upward and downward movement. Like the previous AUV, Pixy camera is used for target detection. It uses open source software, and small in size, affordable and easy to use. The camera processes images from the image sensor and detects objects with certain pattern and color. It can distinguish around 7 different unique colors in 50 frames per second. The raw and processed video can be analyzed by using PixyMon software. The software also provides a panel for input parameter detection, such as contrast and saturation [14]. Table 4 shows the specification of PANTHER AUV.

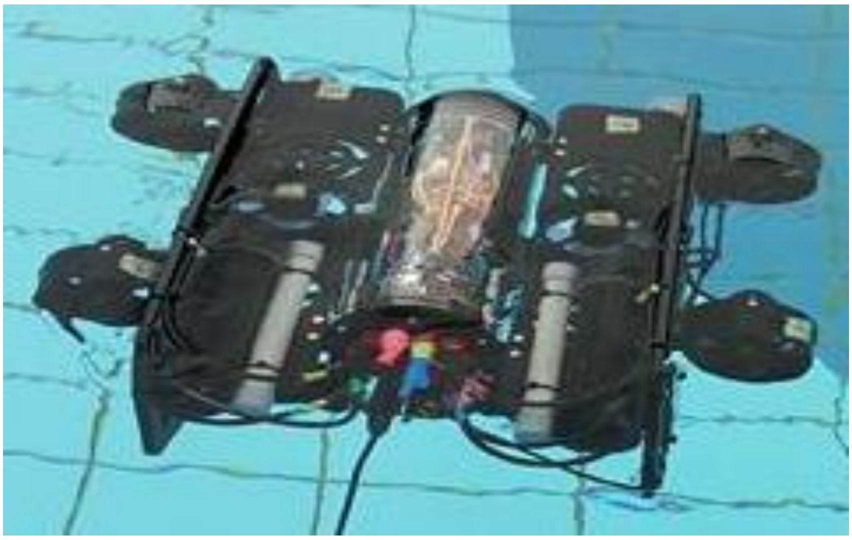

Fig. 5. PANTHER AUV

Table 4
PANTHER AUV specification

Name	Panther AUV
Dimension	50cm x 30cm x 25cm
Weight	8kg
Speed	0.4 m/s (25% of full speed)
Depth	3 to 5 meters
Hull	Poly(methyl methacrylate) (Acrylic)
Frame	black high-density polyethylene (HDPE)
Thrusters	6 thrusters T-200
ESCs	Afro ESC 30A
Controller	Arduino UNO
CPU	8 bit Atmel AVR
Batteries	14.8 V lithium-ion batteries
Sensors	**BNO055/IMU**, Accelerometer, Gyroscope Magnetometer
	Keller LD Bar 100 Pressure Sensor
Camera	Pixy Camera

3.4 PANTHER-J AUV

PANTHER-J AUV (J for Junior), shown in Fig. 6, is an educational derivative of a ROV called OpenROV 2.8 [15]. It comes with the BeagleBone Black single board computer as a processor, and integrated with Arduino MEGA microcontroller for sensor detection and thruster control. The ROV weighs around 2.5 kg with dimensions of 15 cm x 20 cm x 30 cm, as shown in Fig. 5. Inertia measurement unit and pressure sensor are used for movement and depth calibration, which has a single-axis rate gyroscope to measure the yaw rate and a two-axis accelerometer to measure the roll and the pitch. It has depth capability with a maximum operational pressure of 30 bar and an auto-calibrating compass functionality that trues to magnetic north. A 1080p high-definition webcam with 120-degree field-of-view is used in the telemetry system, which is displayed in the OpenROV cockpit through I2C protocols. There are 3 thrusters used for forward, upward and downward movement. Since PANTHER-J only requires basic input output operation, the Arduino UNO is the best option for the AUV controller development, instead of using the original integrated BeagleBone-Arduino MEGA controller. Arduino UNO is the easiest board to be linked to external sensors due to the availability of 3.3v and 5v voltages output. Thus, it can run on any programing in low level C++, with low power consumption. On the contrary, the BeagleBone only operates with 3.3v devices and requires a resistor or other external circuitry to interface to another device with different voltages and requirements. The BeagleBone has slightly higher resolution analog to digital converters which can be useful for more demanding applications such as Linux operating system. It is, however, a great flexible platform that has good input/output features and can easily connect to the network, which can be operated through a web server. **Table 5** shows the specification of PANTHER-J AUV.

Fig. 6. PANTHER-J AUV

Table 5
PANTHER-J AUV specification

Name	PANTHER-J
Dimension	15cm x 20cm x 30cm
Weight	10kg
Speed	0.2 m/s
Depth	3 to 5 meters
Hull	Polyvinyl chloride (PVC)
Frame	Poly(methyl methacrylate) (Acrylic)
Thrusters	3 thrusters
ESCs	Afro ESC 30A
Controller	Arduino UNO
CPU	8 bit Atmel AVR
Batteries	1 Yuasa 12V 8Ah
Sensors	**BNO055/IMU,** Accelerometer Gyroscope, Magnetometer
	MS5837, Depth Sensor
Switch	On/Off
Tether	None
Camera	Not Installed

4. Typical Task in Underwater Competition Navigation Task

A typical task for AUV in any competition is planning and navigation. It is usually a mandatory first task and must be completed before attempting any other tasks. The tasks can be attempted once the AUV achieves certain depth after a dive. In general, the navigation task involves a short swim through a gate in the water, or a long trip with a reference line, or both, as shown in **Fig. 7** and **Fig. 8**.

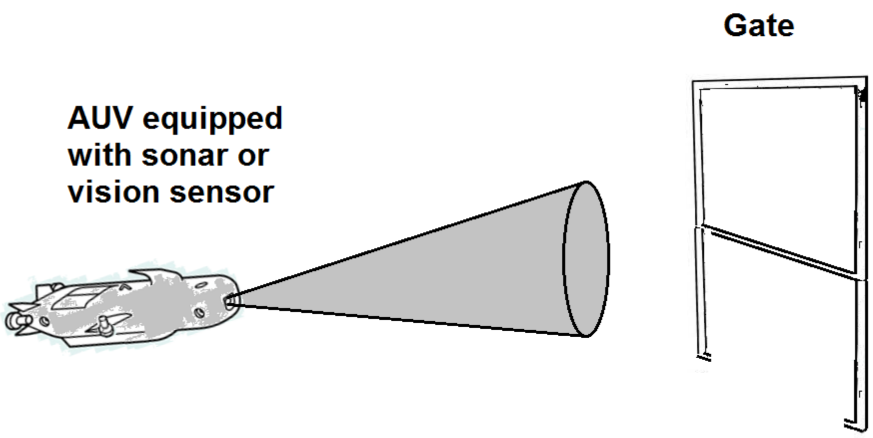

Fig. 7. AUV navigates through a gate using sonar or vision sensor

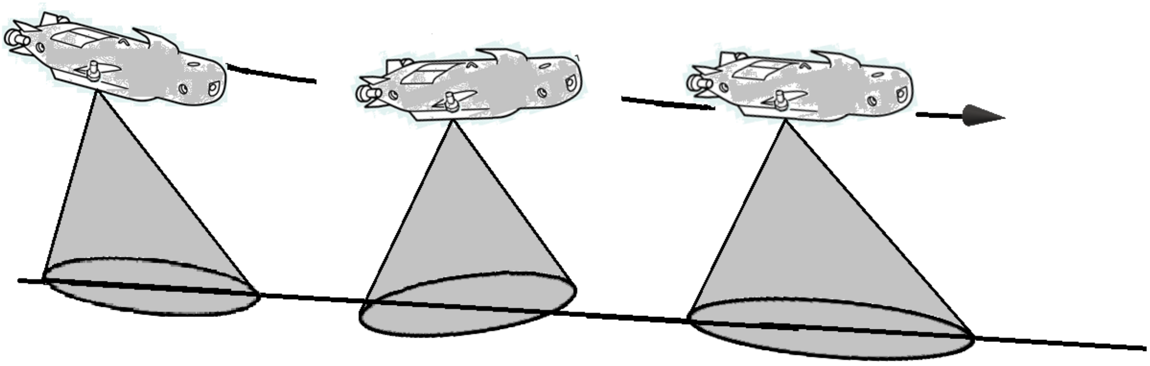

Fig. 8. AUV navigates by following a line in the pool.

The gate may be located anywhere on a horizontal line, parallel to the side of the swimming pool, at a certain distance from the starting point. If the line that the AUV should approach is too far from the starting point, the AUV might wonder in a search mode pattern, by performing a spiral movement towards the line. In some scenario, the AUV fails to follow the line due to low visibility in the water, or get confuse with other objects. Mismatch in programming the thruster operating time, in an on-off, zig-zagging cruising mode, may also cause the AUV to adrift uncontrollably.

4.1 Target Acquisition Task

Figure 9 shows that the AUV needs to drop a ball in one of the drums to successfully complete this task. Points will be awarded based on which drum the ball is dropped into. The aim of the task is to detect and acquire a target among a series of targets at the bottom of the pool, in the designated area.

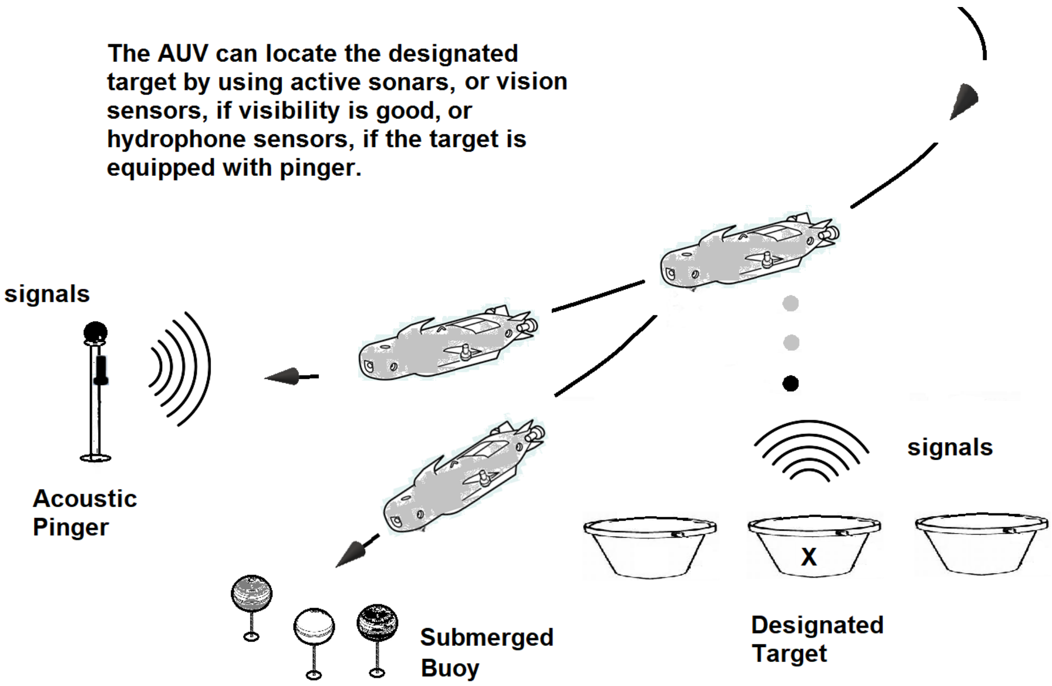

Fig. 9. The AUV in the target acquisition task

The AUV is required to drop a ball or launched a torpedo to the target. Such task requires the AUV to be programmed with a precise coding, and assisted with specialized sensors. The designated target is usually defined by a series of colored targets, usually of submerged buoys, or drums, which are laid down on the floor of the pool. An acoustic pinger is sometimes used in the competition, which requires AUV to be equipped with suitable hydrophones sensors. Other than that, vision sensors, in a form of camera, can also be used, subjected to surrounding visibility. In any cases, sensory perception is the utmost importance for AUV's target acquisition [16]. Sometimes, the task required an event of multiple balls being dropped onto the target. The precise location of the target which contains the acoustic pinger may be randomized between the targets. In the competition, points where given to the AUV that can deliver the ball onto the target accurately, regardless of their specifications. In most competition, dropping the ball into the designated area, or releasing the right submerged buoy will be the utmost challenge, and usually considered for the top three places.

4.2 Object Manipulation Task

In a more difficult task, the AUV are sometimes required to manipulate an object at a designated location or target, as shown in Fig. 10. Usually, this task is only attemptable if the target acquisition has been successfully completed. In some cases, the AUV must first drop the ball or the object, and required to leave the target zone, before it can attempt in reacquiring the object. In a simpler task, some competition already places the object at the designated target zone.

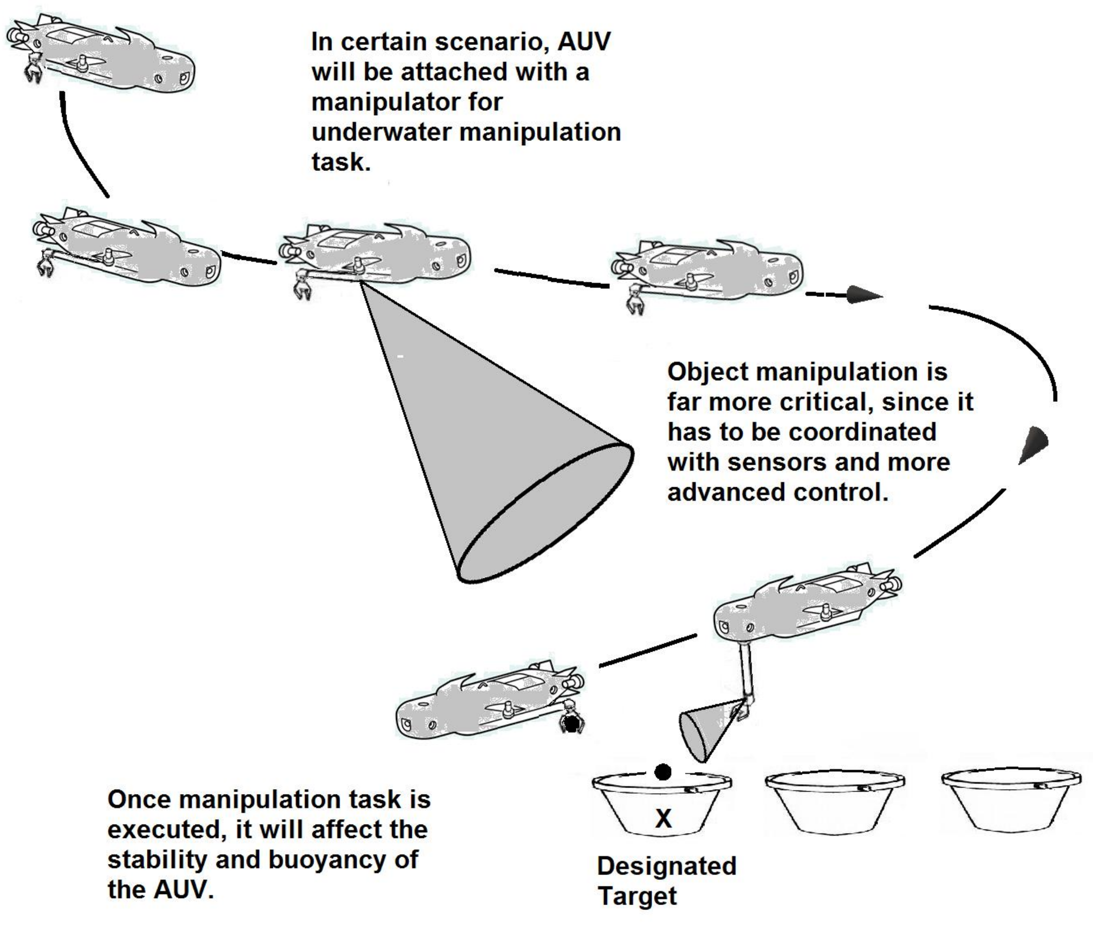

Fig. 10. The AUV in the object manipulation task

If the manipulation task and reacquiring the object is a success, the AUV might be required to hold on to the object till it submerges, in order to successfully complete the task. Underwater manipulation task poses a different challenge upon interested participants due to the fact that they have to take the consideration of the hydrodynamics of the existed underwater surrounding. The demanding and time-consuming tasks demands more complicated approaches, together with the manipulator's design criteria itself. Degree of freedom, workspace extent, load carrying capacity, end-effector, maximum speed and the repeatability and accuracy of the manipulator are some of the criteria that are needed to be considered. Besides that, it is very important to know about the kinematics and dynamic motion of the manipulator [17-18].

5. Lessons learned

In the competition, not all locations of the targets are made known to the participants. Thus, the AUV will have difficulty relying on a fixed navigational strategy. Task in navigation involves sensory perception and avoiding obstacles while attempting to reach some destination. Teamwork, carefully strategized planning, skill and determination will be needed in order to success in the competition.

5.1 Teamwork and Global Networking

SAUVC 2017 was the team's first international competition. The competition is a very good platform for the researchers to communicate with other people around them, share their experience with other university at the international level and most importantly, work as a team. Global networking can be achieved through technical discussion, as shown in Fig. 11, with the experts during the competition. The AUV team usually comprises of 6 persons, whereby 4 members will usually be in the water during the testing session, while the others act as the leader and the lead programmer.

Fig. 11. Discussions with AUV experts [12]

5.2 Mechanical Failure

The team had to endure the entire technical problem during the game. In general, basic technical problem involves leakages. Water leakages can be linked to a non-waterproof kill switch, which was used to switch on and off the AUV. Leakages can be observed by the appearances of bubbles from the switch. Bubbles could be also detected from the controller, battery and ballasts compartment. In some cases, the rate of leakages is small, which can be neglected during the competition. However, the leakages can still affect the stability of the AUV body, and the voltage on the thrusters. Thus, it can cause serious problems to the maneuverability of the AUV. Simultaneously, other components such as the camera may not be used for object recognition due to the leakages found in the camera's casing, if not properly sealed. This will ultimately affect the control of the manipulation processes, which depended on the ability of the manipulator and gripper to receive the signals from the vision sensors.

Fig. 12. On-site troubleshooting [12]

5.3 On-site Troubleshooting

Occasionally, to compensate for all the weaknesses. The team had to do an on-site troubleshooting of their AUV, as shown in Fig. 12. For example, the AUV's manipulator and gripper had to be modified to respond to the given task. Programming was also modified to address the problem in the thrusters. In reality, with malfunction IMU, any AUV can still blindly navigate during the competition. With any luck, it can achieve the basic gate passing navigation task, provided that it can move in a straight line far enough. Besides, the team can conduct several trials of navigation, if the time permits, or if there is no circuitry problem due to leakages.

5.4 Navigation and Planning

Path-planning becomes crucial in getting the AUV from point A to point B. This can be accomplished by generating codes based on known data of the pool. In addition, collision free navigation is achieved in unknown environments by introducing a set of conditional statements prior to vehicle's launch. Codes based on swimming pool data and on mission restrictions can be used to calculate the optimal path. Once the path is calculated, the vehicle can be navigated through the predefined path by the if-else conditional statements. However, error could increase without the use of suitable navigational sensors. Typically, gyroscopic sensors is used to detect the acceleration of the AUV. This is a significant improvement over dead reckoning and is often combined with a doppler velocity log or DVL, which can measure the vehicle's relative velocity. Simultaneously, acoustic transponder beacons can be used to allow the AUV to determine its position. The most common methods are long baseline (LBL) which uses at least two, widely separated transponders and ultra-short baseline (USBL) which generally uses GPS-calibrated transponders on a single surface vessel.

5.5 Localization

It is imperative for the AUV to keep up a feeling of where it is inside the pool. The most common form of localization is known as dead reckoning. This approach is adequate for the competitions. Nonetheless, when the scenario during the competition demand more time and space, the unavoidable internal error to dead reckoning quickly accumulates. Underwater communications are unreliable without access to the global positioning system. In the competition, acoustic pinger is placed at the randomized target. Thus, success in localization will not be achieved, without the use of hydrophones sensors. Right now, the staggering expense of the acoustic sensors impedes the team's effort in improving the AUV's localization capability. Luckily, a precise measurement from the IMU will optimize the input for the microcontroller so that the vehicle has the minimum error through its course. **Fig. 13** shows an AUV is searching to get though the underwater gate. Without a working IMU, the AUV will navigate blindly, and will eventually missed the gate. A low-budget AUV with limited computational power can perform basic path-planning with the help of inertia measurement unit which guides the AUV using a combination of accelerometers and gyroscopes.

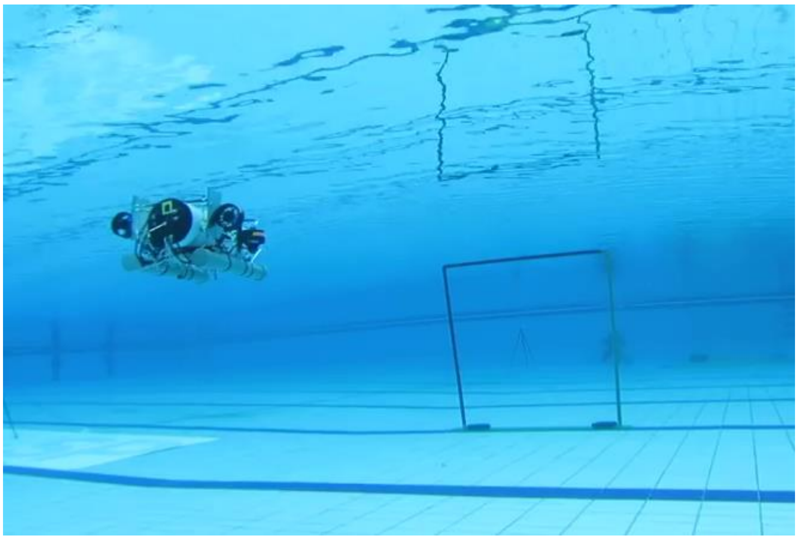

Fig. 13. An AUV is aiming for the gate [19]

Figure 14 shows another type of path-planning. This is called line following navigation. A crude line follower AUV usually applies the switching of the left and right thruster on and off, with a time delay management and a vision sensor, for line following navigation. A better way of detecting the line position, compared to the other simple line-following AUV, is by using a quadratic interpolation technique. A more popular approach is the proportional-integral-derivative (PID) controller, which introduces an error-correction guide for line following navigation. Such approach will require a good programming expert.

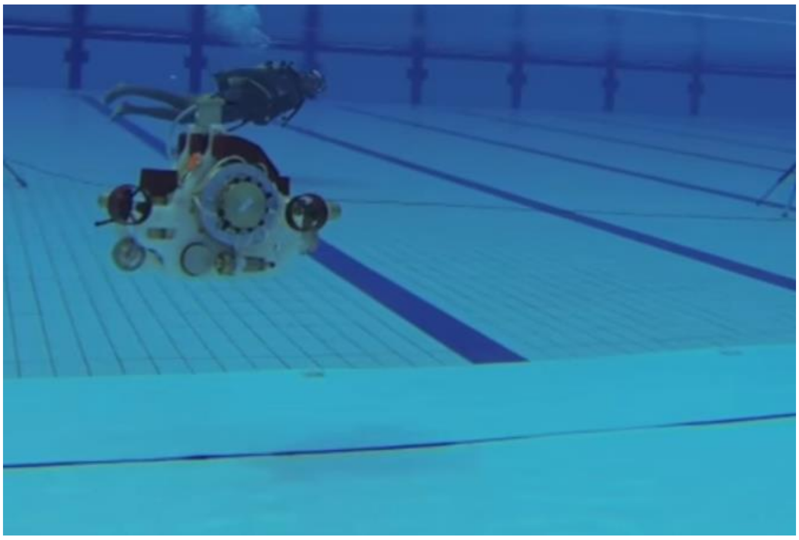

Fig. 14. An AUV is following a line [20]

5.6 Object Recognition and Manipulation

In most autonomous underwater competition, the AUV will be given a series of tasks to complete. The highly anticipate task often includes the manipulation of objects within the pool and moving them from one place to another. Fig. 15 to Fig. 17 show the AUV in object recognition and manipulation task.

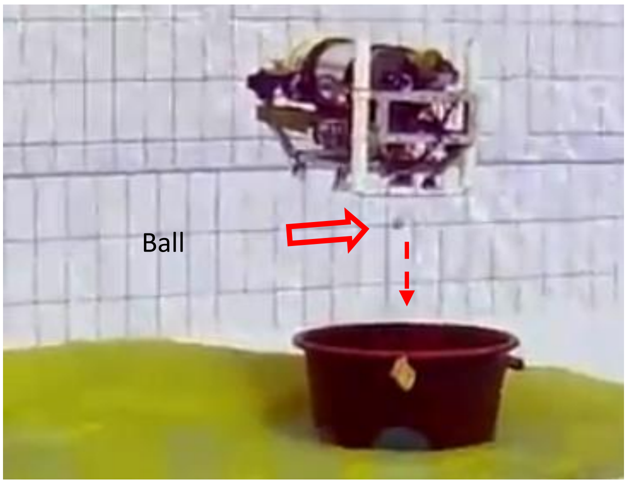

Fig. 15. Ball dropped from an AUV [21]

The team had to rely on the best strategy to achieve the task with optimum winning points, by utilizing sensory capabilities to locate and approach the objects. At the same time, adequate strategy is important to preserve power consumption and energy during the operation of the robotic manipulator. Vision-based systems are a good choice because they provide high resolution images with high speed acquisition at low cost. However, underwater environments may provide color attenuation due to the poor visibility when the distance increases. Underwater manipulator also faces various challenges due to the hydrodynamics elements that existed underwater, which is influenced by the added mass, buoyancy, drag and friction [17].

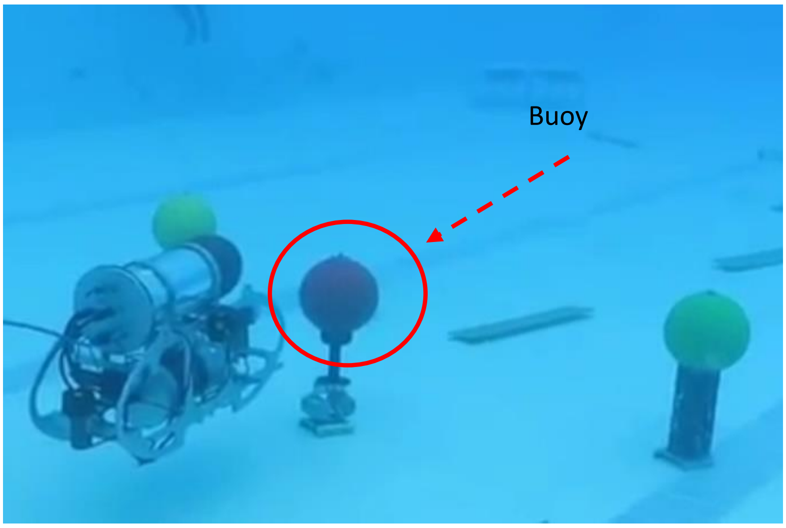

Fig. 16. An AUV successfully hit a target [22]

Fig. 17. An AUV choosing a target [23]

6. Conclusions

Autonomous underwater vehicles (AUV) competitions which are currently organized around the world provide participants with the opportunity to experience the engineering trials and develop skills in AUV technology. This paper describes the development of four AUVs for the competition, known as TUAH 1.0, TUAH 2.0, PANTHER and PANTHER-J. The specifications, data and lesson learned from the competition are discussed and disseminates for technical and knowledge sharing. The team has been supported by the Malaysian Chapter of IEEE Oceanic Engineering Society (OES), IEEE Robotics and Automation Society (RAS), and Universiti Teknikal Malaysia Melaka.

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