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Inertial Sensor Self-Calibration Module for Autonomous Underwater Vehicle Navigation

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Abstract: The Autonomous Underwater Vehicles (AUV) industry is growing dramatically with the increase in the reliability and technical abilities of these vehicles. The vehicles require autonomous guidance and control system in order to perform underwater tasks. The Inertial Sensor Self-Calibration Navigation module is the important mission module that can be implemented into the navigation target, it permits the vehicle to follow preprogrammed trajectories wherever and whenever required. Without this module, the vehicle will not be able to achieve the desired mission. In this work, the Mission module need to be able to identify the task, detect the target, coordinate the state of AUV (attain desired height and yaw angle) and makes decision on path based on mission time elapsed. To navigate this Autonomous Underwater Vehicle (AUV), the navigation module selects Inertial Navigation System (INS). This navigation system used computers, accelerometers, gyroscopes, and sometimes magnetic sensors to calculate the dead reckoning, orientation and velocity (movement direction and speed) moving objects without external reference requirements. The AUV was able to navigate underwater and track underwater object without the need of operator assistance.

Keywords: AUV, Inertial, Navigation, Kalman, INS

1. Introduction

The robotics era has reached a level where the remotely operated vehicle (ROV) industry has become well established with thousands of ROVs being created and deployed since the start of this industry [1]. The ability which enables the communication between the vehicle and operator is one of the main factors that affects whether a vehicle can be designed as an ROV or as an autonomous vehicle [1]. For example, in an environment where communication with the vehicle is limited, autonomous control is required instead of remote control.

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Today, the robotic and AUV industry is growing steadily with the increase in functions and reliability of these vehicles [2]. The main objective of underwater robotic is to make AUVs which is independent and intelligent in making decisions in any situation. In order to accomplish these goals, several researches were being carried out from the entire world with emphasizes on the design, navigation, energy sources, any information related systems.

Autonomous robots can be defined as robots at which can perform any desired tasks in an unstructured condition without any direct human instruction. There were many kinds of an autonomous robots. A high degree of autonomy is which a robot that can operate in extraordinary field conditions such as outer space and sub-sea exploration, where interruption and communication delays is unavoidable. Several modern factory robots can be considered autonomous within their strict confines and direct environment. The workplace of the factory robot is often challenging and can also be unpredictable which require the usage of autonomous robots [1]. A robot can be said fully autonomous in the real world when it has the ability to gain their surrounding information, work for a prolonged period of time without any human intervention, travel from one destination to others without any human assistance, avoid environment which are harmful to human and also able to confront any error without any assistance.

The primary obstacle in making the AUV navigation module a success is to maintain the accuracy of the AUV position over the course of a long time. During long period of missions, prolonged strong currents and other underwater resistance affect the motion of AUV and therefore led to greater inaccuracies [3]. If the position of the AUV is not properly analyzed, the accuracy of the AUV's position will degrade overtime and thus lack of observation and references from external sources makes the AUV navigation becomes impossible.

An Autonomous Underwater Vehicle, AUV navigation module is also considered as a challenging problem due to its rapid attenuation of high frequency signals and obstructed nature of the underwater environment. Most AUV navigation systems uses the inertial navigation as GPS is unable to functions underwater. Some AUVs require the acoustic aiding of a mother ship or by using any underwater acoustic transponders to increase their autonomy of the vehicle [4]. To avoid any costly deployment of underwater transponders, the inertial sensor self-calibration module is a favorable alternative.

An Autonomous Underwater Vehicle (AUV) is a robotic device that move throughout water by a propulsion thruster system, controlled by an onboard computer, and maneuvered in three dimensional underwater [5]. These vehicles require continuous and autonomous guidance in order to perform any underwater tasks efficiently. AUV navigation were performed by using the data provided by proprioceptive or exteroceptive sensors.

However, in practice, and due to their considerable drift, interfere with the magnetic field, the sensor readings are prone to error and unstable [6]. As consequences, will affect the task efficiency and the AUV may be lost. Therefore, one of the suitable modules that can be implemented into the AUV is self-calibration module. The main idea is to improve the performance of integrated sensor reading by reducing the estimation of error and improving the accuracy of range measurements. The module needs to enable accurate positioning and heading during navigation and help the AUV makes decision on path based on mission time elapsed.

2. Methodology

In designing an AUV, a few project phases step should be followed by which is explain in detail in the Figure below. The primary stage emphasizes the main framework of the AUV which is its electrical and mechanical design.

2.1 AUV Design process

The next stages can be divided into two sections which is the first section explains the development of the mechanical design of the AUV. In designing the mechanical design of the AUV, a computer aided designing software is used and the one used in this project is Sketch Up to animate the mechanical design of the AUV. The next part is the designing process of the electrical and electronic parts of the AUV which also includes the wiring design to avoid any magnetic interference from each component to cause any reading error.

Finally, after all mechanical and electrical are installed, the testing process will be done and any major or minor adjustment will be made to correct any error that have come to surfaces while in the testing process. Figure 1 shows the AUV design process.

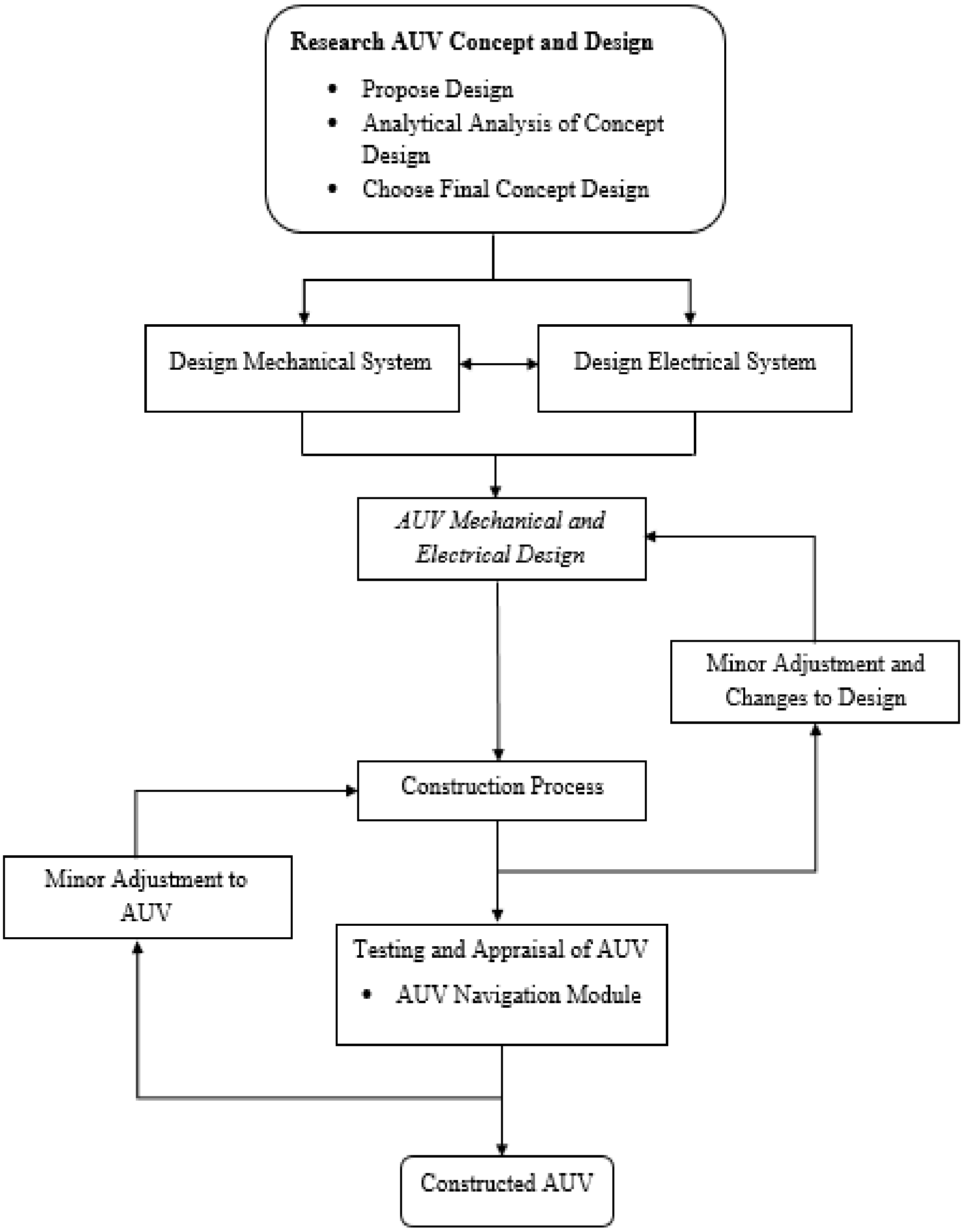

Figure 1: AUV design process

Figure 2 shows the main electronic system structure of the AUV. It can be said that the core of the AUV navigation system is based on the usage of IMU to correct any error reading of the sensor.

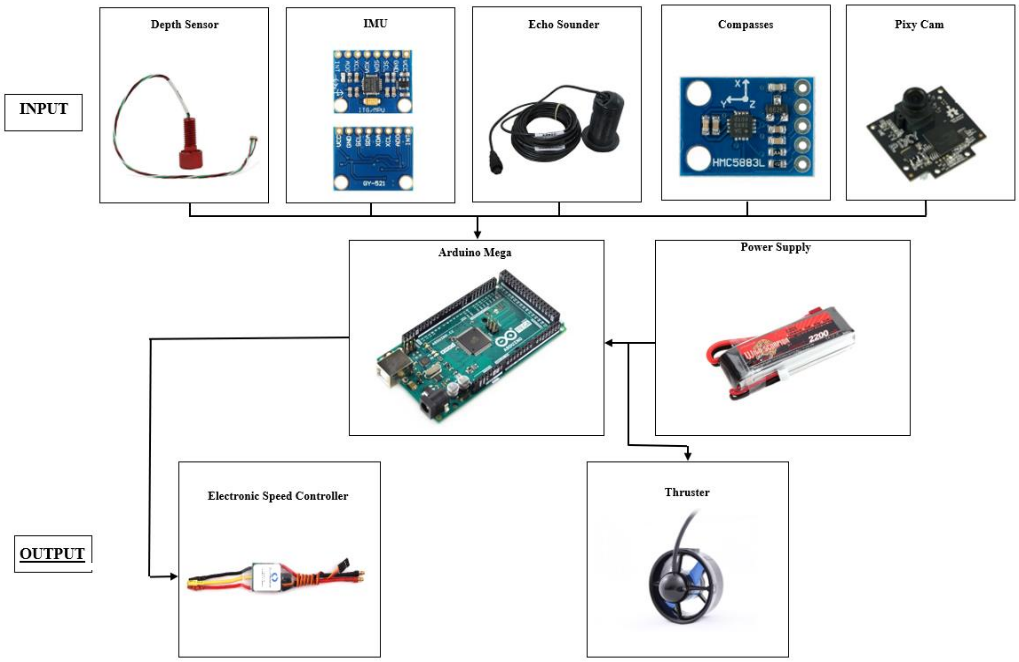

Figure 2: Main electronic system structure

2.2 Kalman Filter

The result of the navigation equations next are analyzed with the integrated aiding sensors using the error state Kalman filter. The basic aiding sensors that are used on the AUV are magnetic compass, depth sensor and echo sounder. The Kalman Filter is a system which estimate the system state from a continuous of unverifiable perceptions using a predict-update cycle. Furtherly, a prediction is estimated for the following state by using the data obtained from the previous and current state.

The Kalman Filter formula process can easily be depicted by the state vector X_{k-1} and covariance vector P_{k-1} at time $k-1$, by using the following condition of the $\mathbf{x}_k = F_{k-1}\mathbf{x}_{k-1} + \mathbf{v}_{k-1}$ where F_{k-1} depicts the physical model and V_{k-1} will portrays the Gaussian uncertainties. After that, the observation of the vector is then characterized as $\mathbf{z}_k = H_k\mathbf{x}_k + \mathbf{w}_k$ where H_k will show the physical model of the observation process and w_k will depicts the uncertainty. The two vectors of V_{k-1} and w_k will be characterized as being produced by zero-mean Gaussian distributions with covariance's Q_{k-1} and R_k. The predictive and updated estimates of the Kalman Filter state vector can be process by the equations:

$$\hat{\mathbf{x}}_{k|k-1} = F_{k-1}\hat{\mathbf{x}}_{k-1} \qquad Eq.1$$

$$\mathrm{P}_{k|k-1} = Q_{k-1} + \mathrm{F}_{k-1}P_{k-1}F_{k-1}^{T} \qquad Eq.2$$

$$\hat{\mathbf{x}}_k = \hat{\mathbf{x}}_{k|k-1} + \mathrm{K}_k(Z_k - H_k\hat{\mathbf{x}}_{k|k-1}) \qquad Eq.3$$

$$\mathrm{P}_k = \mathrm{P}_{k|k-1} - K_k S_k K_k^{T} \qquad Eq.4$$

$\hat{\mathbf{x}}_{k|k-1}$ and $\mathrm{P}_{k|k-1}$ are the predictive estimates values of the state and covariance vectors, $\hat{\mathbf{x}}_k$ and P_k are the updated estimates values and:

$$\mathrm{K}_k = \mathrm{P}_{k|k-1} H_k^{T} S_{k-1} \qquad Eq.5$$

$$\mathrm{S}_k = \mathrm{H}_k \mathrm{P}_{k|k-1} H_k^{T} + R_k \qquad Eq.6$$

Where S_k is the covariance of the ($\mathbf{z}_{k-} H_k \hat{}\mathbf{x}_{k|k-1}$) and K_k the Kalman gain. It shows that the updated estimate $\hat{}\mathbf{x}_k$ contrasts strongly from the predictive estimate $\hat{}\mathbf{x}_{k|k-1}$ by relying upon the distinction of observation $\mathbf{z}_k$ and the predicted observation $H_k \hat{}\mathbf{x}_{k|k-1}$.

The result of this distinction is subject to the Kalman gain and extensive when the difference of the prediction $P_{k|k-1}$ increases higher than the fluctuation of the observation R_k . In this way, the predictive estimations are updated constantly by the Kalman filter by a large amount after the observation values are more certain.

3. Results and Discussion

This chapter present the results that had been taken from the sub module testing. The results recorded are from the preparation of the AUV design preparation and the field test for both land and underwater field testing.

3.1 AUV Design

Figure 3 show the finished installation for the mechanical and also electrical part for the AUV. Each component parts placing is taken into consideration to balance the stability of AUV underwater and also its buoyancy force from the compartment. The inside of the main compartment basically consists of the main circuit, Arduino, camera, IMU sensor, compass module and the power supply for the Arduino while the secondary component is used to store ESC and also the power supply for the ESC only.

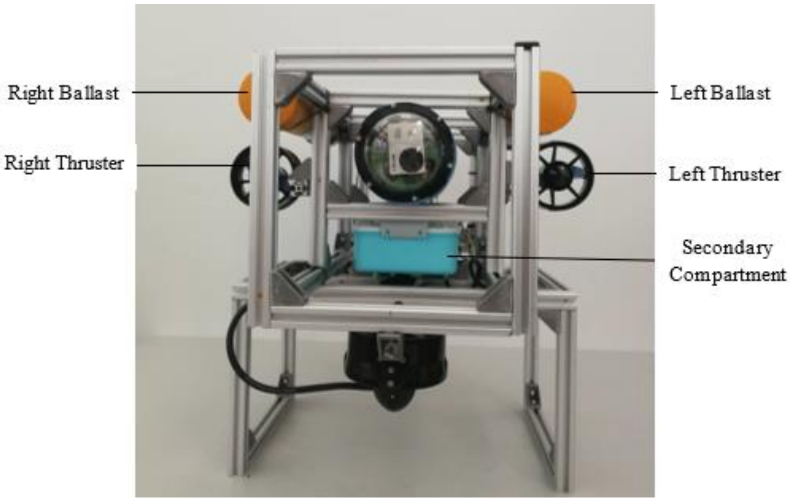

Figure 3: Finished AUV design

3.2 Land Field Test

The land field test for the AUV is a test to check whether the reading for the IMU sensor and compass is accurate and consistent and to check the effect of implementation of Kalman Filter on both the IMU sensor and compass module. The land field test take place on land where the AUV will need to move straight for 10 meter and the IMU sensor and compass module will give a reading with sampling time of 0.5 s. Figure 4 shows the land field test site.

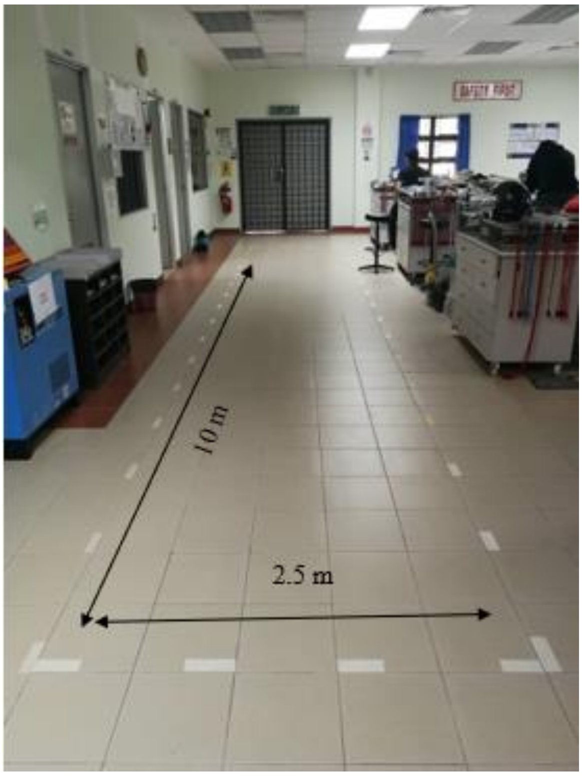

Figure 4: Land field test

Two sets of Tables 1 and Table 2 had been tabulated from the result of land field to consider the difference between the measurement of Euler's angle yaw with and without the usage of Kalman Filter. The highest standard deviation value without the usage of Kalman Filter is 1.4078 with the lowest of 0.4879 while the value of the highest standard deviation with the usage of Kalman Filter is 1.4009 with the lowest of 0. It can be concluded that the value of the yaw angle measurement from the land field test is already consistent enough but with the usage of Kalman Filter the measurement reading consistency increases greatly.

Table 1: Analysis of land field test without Kalman Filter for yaw angle

Distance	Desired Yaw Value (°)	Average (°)	Standard Deviation	Variance	Error (°)
1 m	108	107.6666	0.5163	0.2666	-0.3333
2 m	108	108.2857	0.4879	0.2380	+0.2857
3 m	108	107.7142	0.4879	0.2380	-0.2857
4 m	108	106.8571	0.6900	0.4761	-1.1428
5 m	108	108.1428	1.3451	1.8095	+0.1428
6 m	108	110.4285	0.7867	0.6190	+2.4285
7 m	108	113.3750	1.0606	1.1250	+5.3750
8 m	108	115.7500	0.7071	0.5000	+7.7500
9 m	108	116.2222	0.6666	0.4444	+8.2222
10 m	108	113.3750	1.4078	1.9821	+5.3750

Table 2: Analysis of land field test with Kalman Filter for yaw angle

Distance	Desired K. Yaw Value (º)	Average (º)	Standard Deviation	Variance	Error (º)
1 m	108	107.0000	0	0	-1.0000
2 m	108	107.5714	0.5345	0.2857	-0.4285
3 m	108	107.7142	0.4879	0.2380	-0.2857
4 m	108	106.4285	0.5345	0.2857	-1.5714
5 m	108	107.7428	1.0690	1.1428	-0.2571
6 m	108	110.2857	0.4879	0.2380	+2.2857
7 m	108	112.8750	1.2464	1.5535	+4.8750
8 m	108	115.5000	0.5345	0.2857	+7.5000
9 m	108	115.7777	0.4409	0.1944	+7.7778
10 m	108	113.2500	1.4009	2.2142	+5.2500

The result from the land field test is analyzed using a graphical method. Figure 5 shows the graph of error of yaw angle calculated with and without the usage of Kalman Filter versus travelled distance. The average error for the yaw angle without the usage of Kalman Filter is 3.1341º and the usage of Kalman Filter decreases the average error for yaw angle value until 3.1230º which is as much as 1% of error reduction for the yaw angle. This proven that the Kalman Filter has successfully predict the next state of the AUV thus decreasing the yaw angle value error while increasing its accuracy.

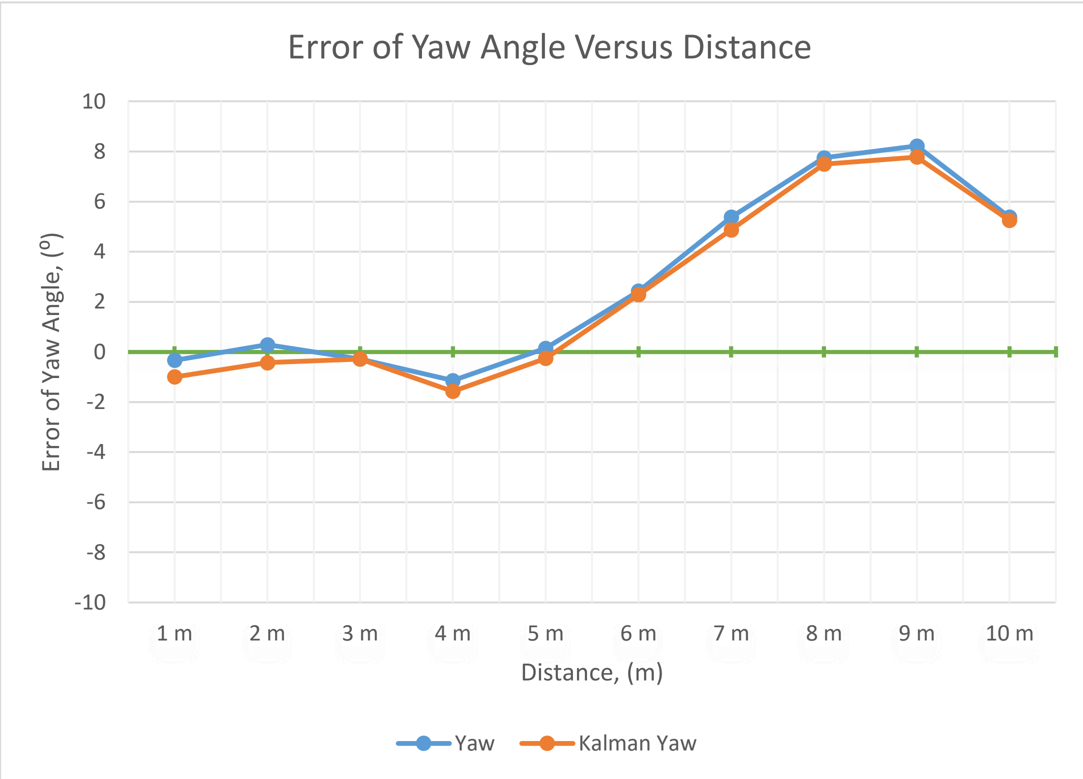

Figure 5: Graph of error of yaw angle versus distance for land field test

3.3 Underwater Field Test

The underwater field test for the AUV is a test to check whether the reading for the IMU sensor and compass is accurate and consistent and to check the effect of implementation of Kalman Filter on both the IMU sensor and compass module. The underwater field test take place underwater where the AUV will need to move straight for also 10 meter like the land field test and the IMU sensor and compass module will also give reading with sampling time of 0.5 s. Figure 6 shows the location for the underwater field test.

Figure 6: Underwater field test site

Two sets of Tables 3 and Table 4 had been tabulated from the result of underwater field test show the difference between the measurement of Euler's angle yaw with and without the usage of Kalman Filter. The highest standard deviation value without the usage of Kalman Filter is 0.9397 with the lowest of 0.4484 while the value of the highest standard deviation with the usage of Kalman Filter is 0.7637 with the lowest of 0.4423. It can be concluded that the value of the yaw angle measurement from the underwater field test is already consistent enough but with the usage of Kalman Filter the measurement reading consistency increases greatly.

Table 3: Analysis of underwater field test without Kalman Filter for yaw value

Distance	Desired Yaw Value (^{o})	Average (^{o})	Standard Deviation	Variance	Error (^{o})
1 m	100	101.0000	0.7172	0.5144	+1.0000
2 m	100	99.6000	0.6396	0.4091	-0.4000
3 m	100	98.9629	0.9397	0.8831	-1.0370
4 m	100	102.6000	0.8504	0.7233	+2.6000
5 m	100	101.7500	0.4484	0.2010	+1.7500
6 m	100	100.6500	0.9333	0.8710	+0.6500
7 m	100	102.5882	0.5557	0.3088	+2.5882
8 m	100	101.2381	0.5732	0.3285	+1.2380
9 m	100	98.2632	0.6882	0.4736	-1.7368
10 m	100	101.1000	0.4893	0.2394	+1.1000

Table 4: Analysis of underwater field test with Kalman Filter for yaw value

Distance	Desired K. Yaw value (º)	Average (º)	Standard Deviation	Variance	Error (º)
1 m	100	100.5833	0.5897	0.3478	+0.5833
2 m	100	99.0667	0.4982	0.2482	-0.9333
3 m	100	99.0370	0.6493	0.4216	-0.9629
4 m	100	101.8400	0.7637	0.5833	+1.8400
5 m	100	101.1250	0.4423	0.1956	+1.1250
6 m	100	100.1500	0.6708	0.45	+0.1500
7 m	100	101.9412	0.5073	0.2573	+1.9411
8 m	100	100.8571	0.5389	0.5732	+0.8571
9 m	100	99.1579	0.4524	0.2046	-0.8421
10 m	100	100.6500	0.4472	0.2	+0.6500

The result from the underwater field test is analyzed using a graphical method. Figure 7 shows the graph of error of yaw angle calculated with and without the usage of Kalman Filter versus travelled distance. The average error for the yaw angle without the usage of Kalman Filter is 1.4100º and the usage of Kalman Filter decreases the average error for yaw angle value until 0.9884º which is as much as 30% of error reduction for the yaw angle. This proven that the Kalman Filter has successfully predict the next state thus decreasing the yaw angle value error while increasing its accuracy.

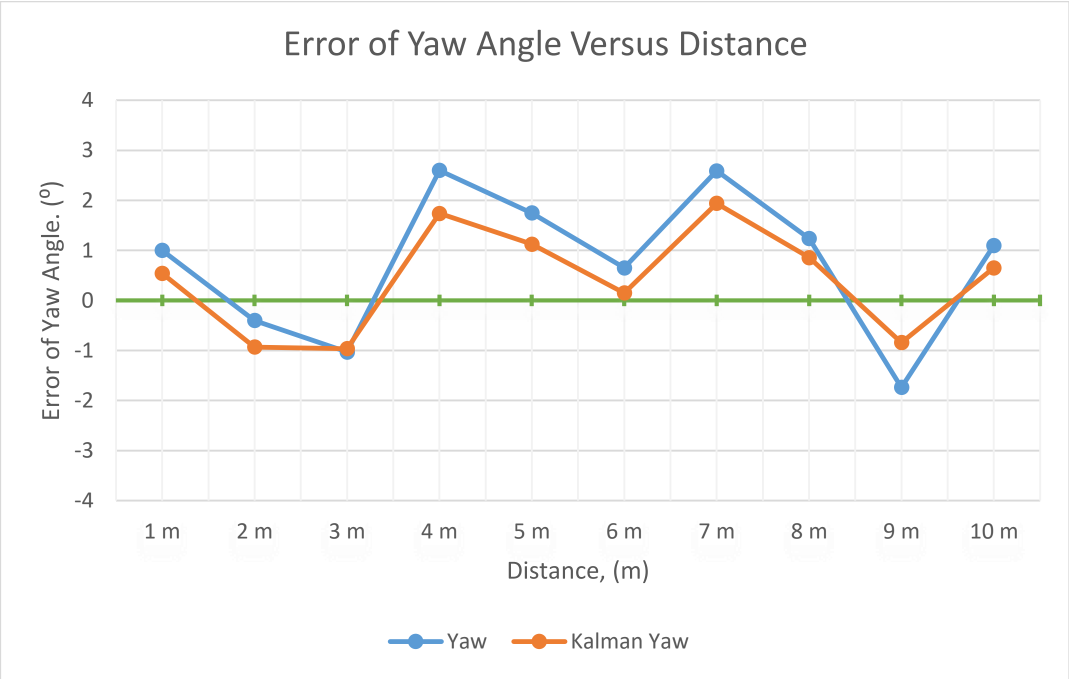

Figure 7: Graph of yaw angle versus distance for underwater field test

4. Conclusion

In this project, several tests had been tested on the AUV both on land and underwater. It can be concluded that the AUV had done a well job without any intervention from the operator. The AUV system consists of multiple essential component that contributes to its operation such as compass module, IMU sensor, pressure sensor, thruster, and pixy cam which are controlled by an Arduino mega microcontroller. AUV will starts functioning when it is submerged underwater.

After that, the IMU and compass module will navigate the AUV underwater with the assist of depth sensor to help the AUV to stay submerged underwater. When the AUV direction changes due to any external interference, the horizontal thrusters will counter the interference force and maintain the AUV on its designated direction. The vertical thruster will simultaneously correct the AUV depth so that it will remain submerged on the desired level of depth. Besides that, the pixy cam also plays an essential role to detect any object underwater and when there is presence of an objects, the AUV will move towards the object. During the test session, several problems had been encountered such as leakage of water inside the main and secondary compartment of the AUV.

This causes imbalance on the AUV buoyant force during operation and the problems were solved by applying extra silicon adhesive to every opening place and vent to prevent water from passing through and short circuit the electronic component. Besides that, the power supply of the AUV are also insufficient which restrict the operational time for the AUV. This issue can be solved by the adding extra power supply so the AUV can operate for a much longer time. From the overall point of view, it can be concluded that the objectives of the AUV project is accomplished which is to design a inertial sensor self-calibration module for AUV and the AUV was able to navigate underwater without the need of operator assistance efficiently.

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