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Navigation System for Smartphone-based Autonomous Underwater Vehicle

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***Abstract*—A navigation system play essential roles in Autonomous Underwater Vehicle (AUV) research. However, controlling an AUV is still challenged with environmental interference, highly nonlinear properties of vehicles, complexity of the hydrodynamics and kinematics. Various methods with complex computation are required to control AUV position. A lot of resource and power is required for complex computation. This paper proposed an alternative method for navigating AUV by combining PID based depth control system and line tracking algorithm. This method was applied on Three Degree of Freedom (3DOF) reference frames dynamic model – Surge, Heave, and Yaw. Meanwhile, the navigation system was used to manage DC motors on SANDY (Smartphone-based Autonomous Underwater System), a micro-size AUV that developed by Robotic – SAS team from Telkom University, Indonesia. Experiments involving simulation and water-tank test indicate that the system is successfully implemented and provide a series of data to use for future works.**

Keywords—AUV; line tracking; navigation; PID; depth control; 3DOF

I. INTRODUCTION

The investigation of Autonomous Underwater Vehicle (AUV) presents both an intriguing and difficult fields of research. The difference between the AUV and the remotely operated vehicle (ROV) is the presence (or absence) of a direct human control on the vehicle [1]. Therefore, controlling an AUV is challenging because of uncertainties in AUV parameters and coefficients, coupled AUV dynamics, and non-linearity of underwater environments due to water current disturbances, hydrodynamics drag forces, and other uncertain coefficients [2][3]. However, controlling an AUV still faces difficulties i.e. environmental disturbance, highly nonlinear behavior of vehicles, complexity of the vehicle hydrodynamics, etc.[3].

AUV navigation control in the nondeterministic underwater environment has become a substantial technology. In the fields of research on the navigation control theories and methods, several works have been carried out. Until recently many researchers have shown interest in the field of AUV navigation system. Their findings and suggestions are reviewed here. Nevertheless, a unified and impeccable architecture has not been established yet, and there are a number of significant theories and technical issues need to be solved and improved.

Previous research from Chemori et. al. [4] presented a depth control method of an AUV. They proposed two depth control schemes: a PID controller and a nonlinear RISE feedback controller. The system is implemented on 4-flipper motor to keeping the buoyancy constant. The results demonstrate that RISE controller is more effective towards environmental disturbances than the PID controller in an open water environment. Nevertheless, the model could only deal within one degree of freedom (depth) and only work on the vehicle that equipped with 4 motor and a depth sensor.

Another method from Hammad et. al. [5] is developed using self-tuning non-linear Fuzzy Proportional Integral Derivative (FPID) for controlling position and speed of MIMO AUV to follow a specific path. In this study, the control scheme in a simulation environment is validated using dynamic and kinematic equations for the AUV model and hydrodynamic damping equations. In the proposed controller, Mamdani fuzzy rules are used to optimize the PID parameters. The results indicate that the FPID controller has a faster response to the reference signal and more stable behavior in a disturbed non-linear environment than conventional PID controller. However, the above-mentioned results address only on kinematic AUV model with eight thrusters.

To support depth control, it is also important to develop another control scheme. Several previous works shows that vision-based control system could be used as an alternative. Miao et. al. (2012) [6] monocular vision system can be installed on an autonomous vehicle for positioning on specific reference i.e. lane. This method can be implemented on AUV control system to adjust its position. This vision system is also can be an alternative method to color sensor system that has been researched by Assaad et.al. (2014) [7]. Previously, several AUV have been controlled using vision system with several image processing method i.e. Randomized Hough Transform edge detection [8], block-based Improved Centre Symmetric Local Binary Pattern on HSV color space [9], multiplicative error state Kalman filter (MESKF) [10], light saturation [11], light beacon [12], and magnetic sensing [13].

This study was conducted using SANDY (***S**martphone-based **A**utonomous u**ND**erwater s**Y**stem*), an underwater vehicle with two thruster DC motor that developed by Robotic – SAS team from Telkom University. This AUV is initially developed to join an annually regional robotic competition in Singapore. The goals of the competition are to explore an L-shaped water tank and pick the cargo on both end section of water tank. SANDY is designed to navigate inside the narrow water tank, it is important to implement a depth control algorithm in order avoiding the obstacle and the tank's wall.

This paper proposes an alternative method for controlling SANDY by combining a PID-based depth control algorithm with line tracking algorithm. This work aims to develop AUV that can be used on shallow water exploration. The rest of this paper is organized as follows. Section 2 describes a proposed navigation control system. Section 3 describes result and discussion from the experiments. Finally, section 4 shows the final remarks of conclusion.

II. Proposed Navigation Control System

The SANDY AUV block diagram is shown in Fig.1. Android-based smartphone is utilized as an image processing platform. Microcontroller system is used for controlling driver motor circuit, actuator and processing proximity sensor data.

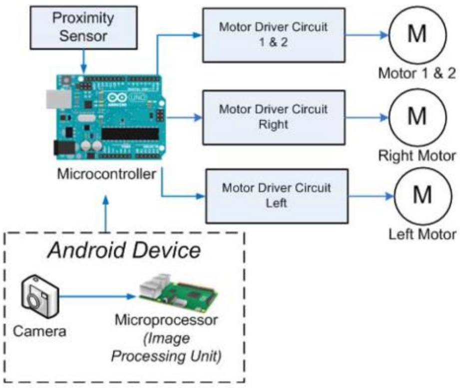

Fig. 1 SANDY block diagram.

A. The Kinematic of AUV

Previous research [3] shows that establishing the parameters of the AUV kinematic model is a complex and resource consuming process. Therefore a simplification process is made to facilitate a modeling. The following assumptions are made as follow:

- The AUV is assumed to be symmetric about three planes since the vehicle operates at relative low speed.
- The AUV's center of gravitation and buoyancy are correctly aligned. The AUV is assumed always remains close to horizontal in all movement.
- AUV movement is assumed move on Three Degree of Freedom (3DOF) – Surge, Heave, and Yaw. Roll and pitch movement are neglected. Fig. 1 shows a proposed 3DOF kinematic model for SANDY.

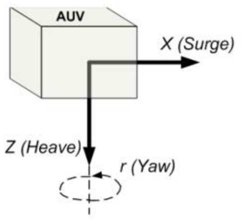

Fig. 2 Proposed kinematic model for 3DOF AUV model.

- Since the AUV is tested on water tank, environmental disturbances also can be neglected.
- AUV is designed with relatively small size (29.6 x 26.66 x 20 cm)

B. First Controller : PID Depth Controller

A model of brushed DC motor is used as an actuator (Fig. 3) and the motor torque and thrust equations are formulated as follows:[5]

$$T = K_t i \quad (1)$$

$$e = K_e \omega \quad (2)$$

$$T = J\frac{d\omega}{dt} + b\omega \quad (3)$$

$$V = iR + L\frac{di}{dt} + e \quad (4)$$

By substituting equation (3) with (4) and converting it using Laplace transformation, the transfer function (equation (5)) between motor's angular velocity $\boldsymbol{\omega}$ and armature voltage $\boldsymbol{V}$ is defined.

$$\frac{\omega(s)}{V(s)} = \frac{K}{S^2LJ + s(JR + Lb) + bR + K^2} \quad (5)$$

Equations (1) to (5) have five unknown parameter. These parameter can be obtained from DC motor datasheet (TABLE I).

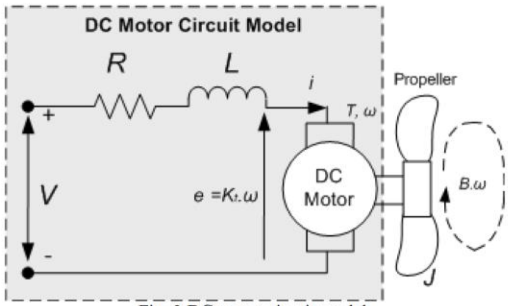

Fig. 3 DC motor circuit model.

TABLE I DC MOTOR PARAMETER FOR SIMULATION

No.	Motor Parameter	Value
1.	Moment of inertia of the rotor (J)	0.1 kg.m^2/s^2
2.	Damping ratio of the mechanical system (b)	0.01 Ns/m^3
3.	Electromotive force constant (K=K_t=K_e)	0.3 Nm/Amp
4.	Electric resistance (R)	2 Ohm
5.	Electric inductance (L)	0.1 H

Data from TABLE I**Error! Reference source not found.** is used to formulate a system's transfer function. The transfer function is defined as follows.

$$\frac{\omega(s)}{V(s)} = \frac{30}{S^2 + 20.1s + 11} \quad (6)$$

$$\frac{C(s)}{R(s)} = \frac{30K_Ds^2 + 30K_Ps + 30K_I}{S^3 + (20.1 + 30K_D)s^2 + (11 + 30K_P)s + 30K_I} \quad (7)$$

Then the controller's transfer function is simulated using MATLAB to obtain an optimal plant's parameter (Fig. 4).

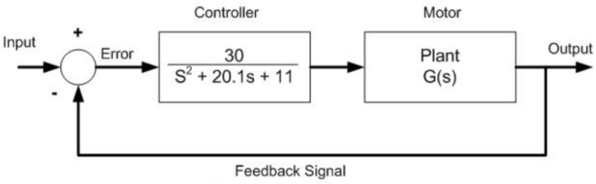

Fig. 4 DC motor transfer function.

Depth controller block diagram is shown in Fig. 5. PID algorithm is adopted to depth holding navigation process. The proportional component is approximately proportional to the vehicle position. If the vehicle is precisely centered on the specific depth, a proportional value will be 0. The integral component value records a sum of all of the values of the proportional term that were recorded since the vehicle started running. Meanwhile, the derivative component will control the rate of change of the proportional value and typically used for controlling the vehicle's speed.

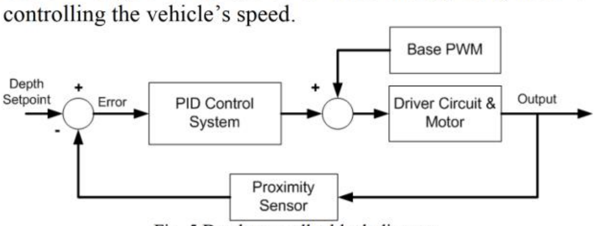

Fig. 5 Depth controller block diagram.

When the vehicle is activated, calibration process will be running by establishing the set point depth's value. Then, proximity sensor's data is read by microcontroller to record the current depth value. Error value is the difference between of the two values. If the output value less than zero, the vehicle's position is above the set point value and automatically dropping down to the set point. Otherwise, when the output value more than zero, the vehicle position is below the set point value and the vehicle automatically rising up. More detailed flowchart is shown in Fig. 10.

C. Second Controller : Line Tracking

Previous research from Tan and Mae (2013) [14] demonstrate a convenient algorithm for the recognition of lane markings and the estimation of vehicle's lateral position and orientation. The algorithm is performed on the coordinate of detected lines only, not the whole image pixels. It only searches for two parallel lines with a particular distance to each other. The most intriguing part from their works is the color matching that only checks the color of the pixels around the lane marking candidates. This idea can be used as the basis for AUV line tracking algorithm especially when SANDY is tested on water tank with 5-cm yellow line on its wall. This controller will be used to control AUV's movement on surge and yaw plane.

TABLE II. SMARTPHONE SPECIFICATION

Part Name	Specification
Type	Asus Zenfone 5 A500CG
Operating System	Android 4.3 (Jelly Bean), upgradable to 5.0.2 (Lollipop)
Chipset	Intel Atom Z2580 Dual-core 2.0 GHz
GPU	PowerVR SGX544MP2
RAM	2 GB
Camera	8 MP, f/2.0, autofocus, LED flash
Video	Max. 1080p@30fps
Internal Memory	8/16/32 GB, 2 GB RAM
Dimension	29.6 x 26.66 x 15.5 cm

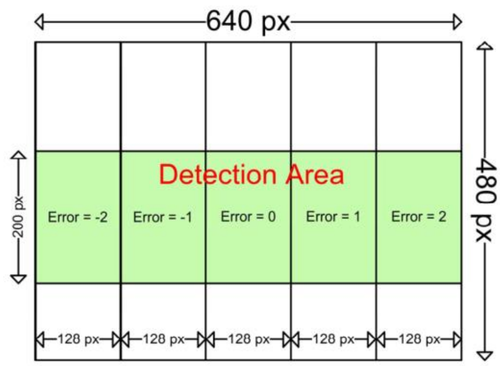

Fig. 6 Image mapping system.

For line tracking process, OpenCV library is used for developing a smartphone application by utilizing on-board camera. Smartphone specification that used in this paper is shown in TABLE II. The camera's resolution is set on 640 x

480 pixel and frame rate between 25-30 fps for optimal computation. To calculate error, the image mapping system is designed (Fig. 6). The mapping system is divided into five area of error. Value 0 for set point and the others for deviation. The result from mapping is processed by line tracking algorithm. Line tracking system block diagram is shown in Fig. 7.

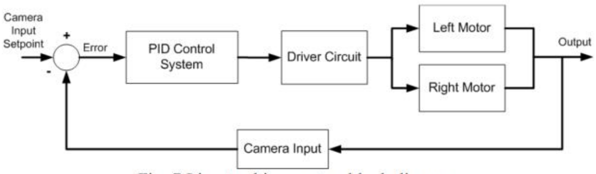

Fig. 7 Line tracking system block diagram.

The process flow of the object detection program begins with importing OpenCV libraries, camera initialization and USB ports. Then, the video is captured and processed as RGB frame. The RGB frame is converted to HSV frames. After that, the process will search all contour on threshold frame. If contour is found, a rectangular shape (Fig. 8) will follow the edge of the contour. Then, the program will calculate the position of the central point coordinates with the following formula.

$$x_P = \frac{(x_2 - x_1)}{2} \quad (8)$$

$$y_P = \frac{(y_2 - y_1)}{2} \quad (9)$$

The central point data is sent to microcontroller as a set point movement. The AUV position in the water will be adjusted relative to the position of the point. The illustration of the central point position is shown in Fig. 8.

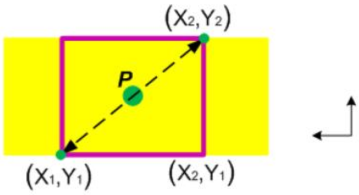

Fig. 8 Center point calculation.

The line tracking program mechanism for AUV movement is described as follows.

a. Central point becomes the reference of vehicle to move forward (Fig. 9a).

b. If there is a left or right corner, the program will automatically redirect the AUV (Fig. 9b).

c. When the camera detects an object other than the yellow color, the program is designed to continue searching for the nearest yellow object (Fig. 9c).

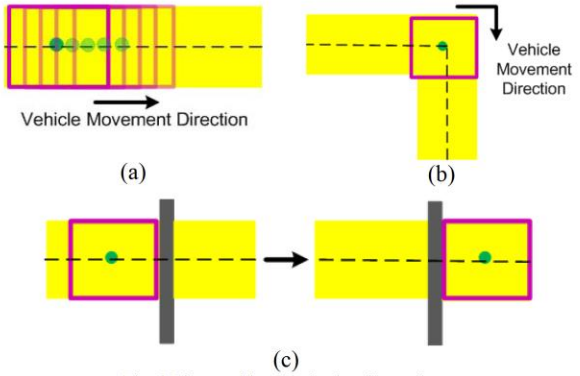

Fig. 9 Line tracking mechanism ilustration.

The flowchart of a combined controller system is shown in Fig. *10*.

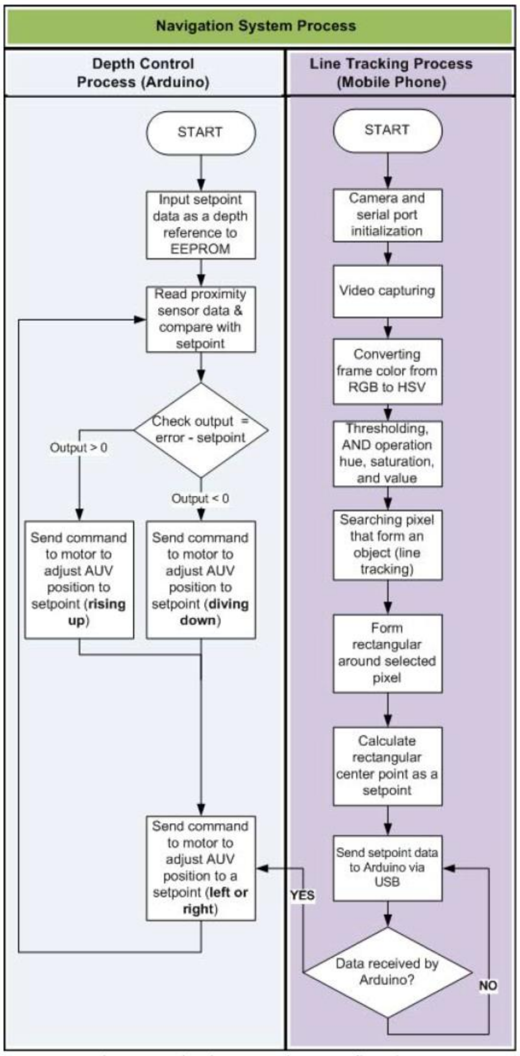

Fig. 10 Navigation control system flowchart.

III. Experiment Results and Analysis

A. PID Depth Controller Results

The DC motor transfer function (from Fig. 4) have been simulated and tuned in for optimal PID parameter. The step response of transfer function is shown in Fig. 11.

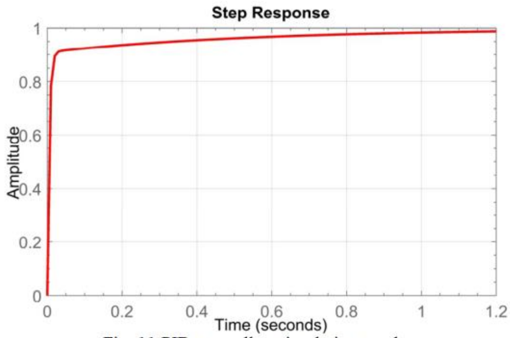

Fig. 11 PID controller simulation result.

From this simulation, three optimal PID parameter is obtained as follows (TABLE III).

TABLE III. Optimal PID Parameter from Simulation

PID Parameter	Value
K_p	15
K_i	6
K_d	6
Rise time	0.021 s
Settling time	Min.: 0.9002 s Max: 0.9971 s
% of overshoot	0 %

The vehicle is tested in an L-shaped tank of dimension: 142.5cm x 142.5 cm x 50 cm. There are two rectangular window frames, with cm thickness on each section of the tank 50 cm from the end of the tank. The center section of the tank will have a bump which is 12.5mm in height.

The PID parameter (K_p, K_i, and K_d) from TABLE III is used on depth control program to optimize AUV maneuver. Illustration of the process can be seen in Fig. 12.

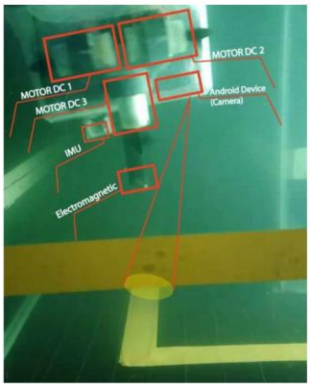

Fig. 12 AUV positioning in the tank.

After the calibration process is complete, the AUV will then move down the aquarium with reference to the yellow line.

TABLE IV. Depth Holding Experiment Result

Time (second)	Setpoint Depth = 7 cm	
	Actual Depth (cm)	*Deviation (cm)*
0.6622513	5	-2
1.0032947	5	-2
1.9924183	6	-1
2.9275359	6	-1
4.0876813	7	0
5.0428017	7	0
5.9269128	8	1
7.0200502	9	2
8.0341767	12	5
9.0573049	7	0
10.0944356	7	0
11.7076378	6	-1
13.0156771	5	-2
13.8977871	6	-1

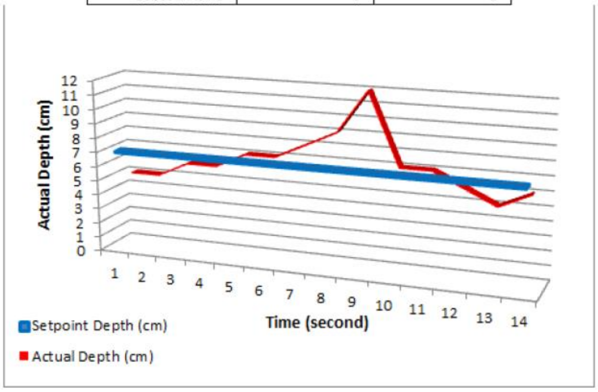

Fig. 13 AUV depth's variation against setpoint value.

The experiment results indicate that PID algorithm is successfully used for depth holding. Based on the plot of the graph in Fig. 13, there are variations of depth value against set point but within a tolerable condition. There is a deviation that varies with a fairly small range (error average 1.28 cm).

B. Line Tracking Experiment Results

The results are shown on TABLE V. When the central point (green dot) position is precisely on center of the line, the vehicle is automatically move forward following the line (Fig. 14). If the dot position is on the right position, system will adjust the position to the left according to the set point. Otherwise, when the dot position is on the left, system will adjust the position to the right according to the set point.

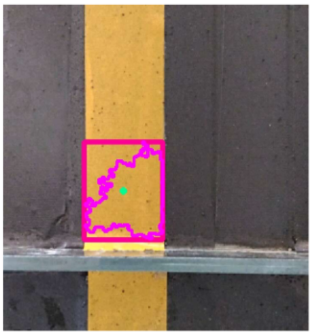

Fig. 14 Line tracking display.

To measure the accuracy of the line tracking system, error detection for three different positions according to Fig. 6 is evaluated. At each position, the motor duty cycle is observed. TABLE V indicate that on every error value change from 0 to 1 and -1, the AUV's motor duty cycle change its value. This value indicates that the controller can calculate the effective speed using algorithm to adjust the position.

TABLE V. LINE TRACKING ERROR DETECTION AREA EXPERIMENT

Time base (s)	**Error Value (PV)**	**Set point = 40% duty cycle**	
		Left Motor (% duty cycle)	**Right Motor (% duty cycle)**
0	0	40	40
1	0	40	40
2	0	40	40
3	1	29.41	50.59
4	1	28.24	51.76
5	0	44.71	35.29
6	-1	50.59	29.41
7	-1	51.76	28.24
8	0	35.29	44.71
9	0	40	40
10	1	29.41	50.59

IV. CONCLUSION

This paper successfully presented an alternative method for developing AUV control system by combining smartphone-based image processing system and proximity sensor. Firstly, PID algorithm can successfully implemented as a depth holding program on AUV within 1.28 cm error average. Secondly, line tracking application can be used to control AUV's motor to adjust its position automatically.

A combination between depth controller and line tracking controller had been designed and implemented in SANDY AUV. The effect of positive buoyancy on surge, yaw, and heave dynamics is discussed and handled directly by the proposed controller scheme. Experimental results indicate that the control system is effective in controlling the depth of the AUV with negligible steady state error.

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***Abstract*—A navigation system for AUV is required by an Autonomous Underwater Vehicle (AUV) as an "eyes". However, controlling an AUV still faces difficulties environmental disturbance, highly nonlinear behavior of vehicles, complexity of the vehicle hydrodynamics. Various methods with complex computation are required to control AUV position. A lot of resource and power is required to do the complex computation. This paper proposed an alternative method for navigating AUV by combining PID based depth control system and line tracking algorithm. This method was applied on Three Degree of Freedom (3DOF) reference frames dynamic model – Surge, Heave, and Yaw. Meanwhile, the navigation system was used to manage DC motors on SANDY (Smartphone-based Autonomous Underwater System), a micro-size AUV that developed by Robotic – SAS team from Telkom University, Indonesia. Experiments involving pre-test simulation and water-tank test indicate that the system is successfully implemented and provide a series of data to use on later study.**

Keywords*—*AUV; line tracking; navigation; PID; depth control; 3DOF

I. Introduction

The investigation of Autonomous Underwater Vehicle (AUV) presents both an intriguing and difficult fields of research. The difference between the AUV and the remotely operated vehicle (ROV) is the presence (or absence) of a direct human control on the vehicle [1]. Therefore, controlling an AUV is challenging because of uncertainties in AUV parameters and coefficients, coupled AUV dynamics, and non-linearity of underwater environments due to water current disturbances, hydrodynamics drag forces, and other uncertain coefficients [2][3]. However, controlling an AUV still faces difficulties i.e. environmental disturbance, highly nonlinear behavior of vehicles, complexity of the vehicle hydrodynamics, etc.[3].

AUV navigation control in the nondeterministic underwater environment has become a substantial technology. In the fields of research on the navigation control theories and methods, several works have been carried out. Until recently many researchers have shown interest in the field of AUV navigation system. Their findings and suggestions are reviewed here. Nevertheless, a unified and impeccable architecture has not been established yet, and there are a number of significant theories and technical issues need to be solved and improved.

Previous research from Chemori et. al. [4] presented a depth control method of an AUV. They proposed two depth control schemes: a PID controller and a nonlinear RISE feedback controller. The system is implemented on 4-flipper motor to keeping the buoyancy constant. The results demonstrate that RISE controller is more effective towards environmental disturbances than the PID controller in an open water environment. Nevertheless, the model could only deal within one degree of freedom (depth) and only work on the vehicle that equipped with 4 motor and a depth sensor.

Another method from Hammad et. al. [5] is developed using self-tuning non-linear Fuzzy Proportional Integral Derivative (FPID) for controlling position and speed of MIMO AUV to follow a specific path. In this study, the control scheme in a simulation environment is validated using dynamic and kinematic equations for the AUV model and hydrodynamic damping equations. In the proposed controller, Mamdani fuzzy rules are used to optimize the PID parameters. The results indicate that the FPID controller has a faster response to the reference signal and more stable behavior in a disturbed non-linear environment than conventional PID controller. However, the above-mentioned results address only on kinematic AUV model with eight thrusters.

To support depth control, it is also important to develop another control scheme. Several previous works shows that vision-based control system could be used as an alternative. Miao et. al. (2012) [6] monocular vision system can be installed on an autonomous vehicle for positioning on specific reference i.e. lane. This method can be implemented on AUV control system to adjust its position. This vision system is also can be an alternative method to color sensor system that has been researched by Assaad et.al. (2014) [7]. Previously, several AUV have been controlled using vision system with several image processing method i.e. Randomized Hough Transform edge detection [8], block-based Improved Centre Symmetric Local Binary Pattern on HSV color space [9], multiplicative error state Kalman filter (MESKF) [10], light saturation [11], light beacon [12], and magnetic sensing [13].

This study was conducted using SANDY (***S**martphone-based **A**utonomous u**ND**erwater s**Y**stem*), an underwater vehicle with two thruster DC motor that developed by Robotic – SAS team from Telkom University. This AUV is initially developed to join an annually regional robotic competition in Singapore. The goals of the competition are to explore an L-shaped water tank and pick the cargo on both end section of water tank. SANDY is designed to navigate inside the narrow water tank, it is important to implement a depth control algorithm in order avoiding the obstacle and the tank's wall.

This paper proposes an alternative method for controlling SANDY by combining a PID-based depth control algorithm with line tracking algorithm. This work aims to develop AUV that can be used on shallow water exploration. The rest of this paper is organized as follows. Section 2 describes a proposed navigation control system. Section 3 describes result and discussion from the experiments. Finally, section 4 shows the final remarks of conclusion.

II. Proposed Navigation Control System

The SANDY AUV block diagram is shown in Fig.1. Android-based smartphone is utilized as an image processing platform. Microcontroller system is used for controlling driver motor circuit, actuator and processing proximity sensor data.

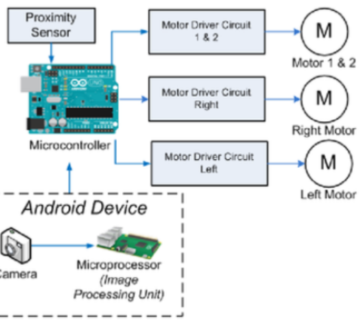


Fig. 1 SANDY block diagram.

A. The Kinematic of AUV

Previous research [3] shows that establishing the parameters of the AUV kinematic model is a complex and resource consuming process. Therefore a simplification process is made to facilitate a modeling. The following assumptions are made as follow:

- The AUV is assumed to be symmetric about three planes since the vehicle operates at relative low speed.
- Since the center of gravitation and center of buoyancy are correctly in right order aligned, the AUV remains close to horizontal in all maneuvers and stabilizes itself.
- AUV movement is assumed move on Three Degree of Freedom (3DOF) – Surge, Heave, and Yaw. Roll and pitch movement are neglected. Fig. 1 shows a proposed 3DOF kinematic model for SANDY.

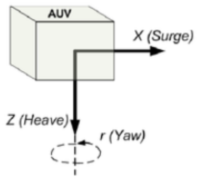


Fig. 2 Proposed kinematic model for 3DOF AUV model.

- Since the AUV is tested on water tank, environmental disturbances also can be neglected.
- AUV is designed with relatively small size (29.6 x 26.66 x 20 cm)

B. First Controller : PID Depth Controller

The thruster can be divided into two parts which are the motor and the propeller as shown in *Fig. 3*. A model of brushed DC motor is used as an actuator and the motor torque and thrust equations are formulated as follows:[5]

$$T = K_t i \quad (1)$$

$$e = K_e \omega \quad (2)$$

$$T = J\frac{d\omega}{dt} + b\omega \quad (3)$$

$$V = iR + L\frac{di}{dt} + e \quad (4)$$

By substituting equation (3) with (4) and converting it using Laplace transformation, the transfer function (equation (5)) between motor's angular velocity ω and armature voltage V is defined.

$$\frac{\omega(s)}{V(s)} = \frac{K}{S^2LJ + s(JR + Lb) + bR + K^2} \quad (5)$$

Equations (1) to (5) have five unknown parameter. These parameter can be obtained from DC motor datasheet (*TABLE I*)

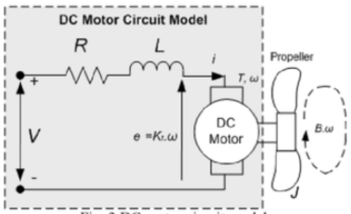


Fig. 3 DC motor circuit model.

TABLE I DC MOTOR PARAMETER FOR SIMULATION

No.	Motor Parameter	Value
1.	Moment of inertia of the rotor (J)	0.1 kg.m^2/s^2
2.	Damping ratio of the mechanical system (b)	0.01 Ns/m^3
3.	Electromotive force constant ($K=K_t=K_e$)	0.3 Nm/Amp
4.	Electric resistance (R)	2 Ohm
5.	Electric inductance (L)	0.1 H

Data from **Error! Reference source not found.** is used to formulate a system's transfer function. The transfer function is defined as follows.

$$\frac{\omega(s)}{V(s)} = \frac{30}{S^2 + 20.1s + 11} \quad (6)$$

$$\frac{C(s)}{R(s)} = \frac{30K_D s^2 + 30K_P s + 30K_I}{S^3 + (20.1 + 30K_D)s^2 + (11 + 30K_P)s + 30K_I} \quad (7)$$

Then the controller's transfer function is simulated using MATLAB to obtain an optimal plant's parameter (*Fig. 4*).

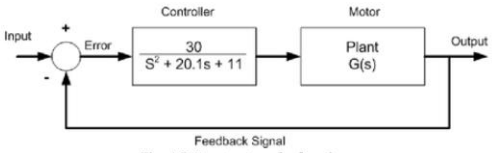


Fig. 4 DC motor transfer function.

Depth controller block diagram is shown in *Fig. 5*. PID algorithm is adopted to depth holding navigation process. The proportional component is approximately proportional to the vehicle position. If the vehicle is precisely centered on the specific depth, a proportional value will be 0. The integral component value records a sum of all of the values of the proportional term that were recorded since the vehicle started running. Meanwhile, the derivative component will control the rate of change of the proportional value and typically used for controlling the vehicle's speed.

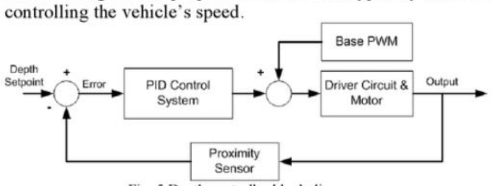


Fig. 5 Depth controller block diagram.

When the vehicle is activated, calibration process will be running by establishing the set point depth's value. Then, proximity sensor's data is read by microcontroller to record the current depth value. Error value is the difference between of the two values. If the output value less than zero, the vehicle's position is above the set point value and automatically dropping down to the set point. Otherwise, when the output value more than zero, the vehicle position is below the set point value and the vehicle automatically rising up. More detailed flowchart is shown in *Fig. 9*.

C. Second Controller : Line Tracking

Previous research from Tan and Mae (2013) [14] demonstrate a convenient algorithm for the recognition of lane markings and the estimation of vehicle's lateral position and orientation. The algorithm is performed on the coordinate of detected lines only, not the whole image pixels. It only searches for two parallel lines with a particular distance to each other. The most intriguing part from their works is the color matching that only checks the color of the pixels around the lane marking candidates. This idea can be used as the basis for AUV line tracking algorithm especially SANDY is tested on water tank with 5-cm yellow line on its wall.

TABLE II. SMARTPHONE SPECIFICATION

Part Name	Specification
Type	Asus Zenfone 5 A500CG
Operating System	Android 4.3 (Jelly Bean), upgradable to 5.0.2 (Lollipop)
Chipset	Intel Atom Z2580 Dual-core 2.0 GHz
GPU	PowerVR SGX544MP2
RAM	2 GB
Camera	8 MP, f/2.0, autofocus, LED flash
Video	1080p@30fps
Internal Memory	8/16/32 GB, 2 GB RAM
Dimension	29.6 x 26.66 x 15.5 cm

For line tracking process, OpenCV library is used for developing a smartphone application by utilizing on-board camera. Smartphone specification that used in this paper is shown in *TABLE II*. The camera's resolution is set on 352 x 288 pixel and frame rate between 25-30 fps for optimal computation.

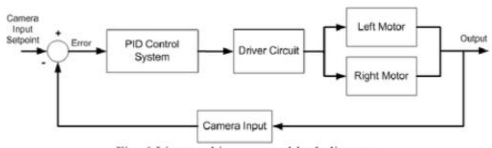


Fig. 6 Line tracking system block diagram.

The process flow of the object detection program begins with importing OpenCV libraries, camera initialization and USB ports. Then, the video is captured and processed as RGB frame. The RGB frame is converted to HSV frames. After that, the process will search all contour on threshold frame. If contour is found, a rectangular shape (*Fig. 7*) will follow the edge of the contour. Then, the program will calculate the position of the central point coordinates with the following formula.

$$x_P = \frac{(x_2 - x_1)}{2} \quad (8)$$

$$y_P = \frac{(y_2 - y_1)}{2} \quad (9)$$

The central point data is sent to microcontroller as a set point movement. The AUV position in the water will be adjusted relative to the position of the point. The illustration of the central point position is shown in Fig. 7.

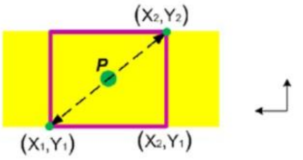


Fig. 7 Center point calculation.

The line tracking program mechanism for AUV movement is described as follows.

a. Central point becomes the reference of vehicle to move forward (*Fig. 8*a).

b. If there is a left or right corner, the program will automatically redirect the AUV(*Fig. 8*b).

c. When the camera detects an object other than the yellow color, the program is designed to continue searching for the nearest yellow object (*Fig. 8*c).

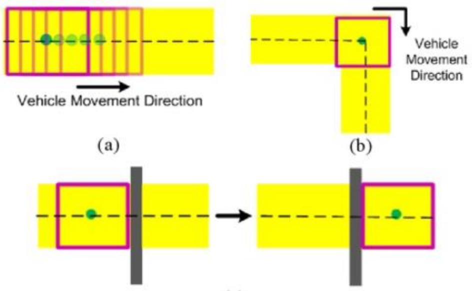


Fig. 8 Line tracking mechanism ilustration.

The flowchart of a combined controller system is shown in **Error! Reference source not found.**.

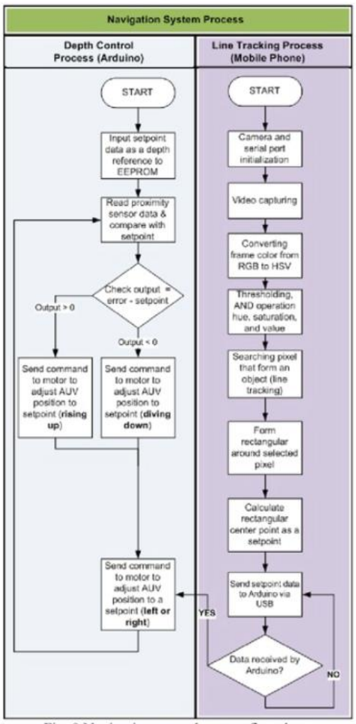


Fig. 9 Navigation control system flowchart.

III. Experiment Results and Analysis

A. PID Depth Controller Results

The DC motor transfer function (from *Fig. 4*) have been simulated and tuned in for optimal PID parameter. The step response of transfer function is shown in *Fig. 10*.

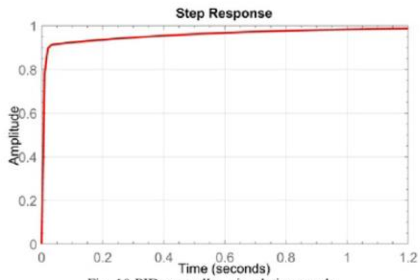


Fig. 10 PID controller simulation result.

From this simulation, three optimal PID parameter is obtained as follows (*Table III*).

TABLE III OPTIMAL PID PARAMETER FROM SIMULATION

PID Parameter	Value
Kp	15
Ki	6
Kd	6
Rise time	0.021 s
Settling time	Min.: 0.9002 s Max: 0.9971 s
% of overshoot	0 %

The vehicle is tested in an L-shaped tank of dimension: 142.5cm x 142.5 cm x 50 cm. There are two rectangular window frames, with cm thickness on each section of the tank 50 cm from the end of the tankSee Figure 2 for detailed dimensions. The centre section of the tank will have a bump which is 12.5mm in height.

The calibration process is done to perform the zeroing process or adjusting the coordinates of point 0 of the line. This process is done at the end of the aquarium testing. After the calibration process is complete, the AUV will the move down the aquarium with reference to the yellow line. Illustration of the process can be seen in Figure 12 below.

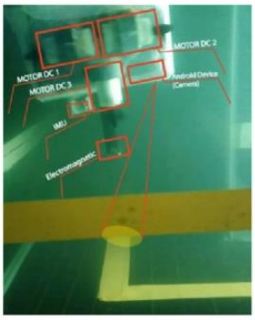


Fig. 11 AUV positioning in the tank.

TABLE IV. DEPTH HOLDING EXPERIMENT RESULT

Time (second)	Setpoint Depth = 7 cm	
	Actual Depth (cm)	*Deviation (cm)*
0.6622513	5	-2
1.0032947	5	-2
1.9924183	6	-1
2.9275359	6	-1
4.0876813	7	0
5.0428017	7	0
5.9269128	8	1
7.0200502	9	2
8.0341767	12	5
9.0573049	7	0
10.0944356	7	0
11.7076378	6	-1
13.0156771	5	-2
13.8977871	6	-1

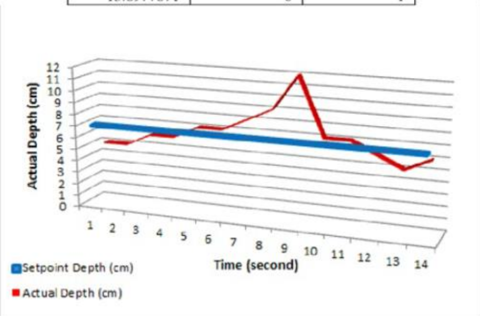


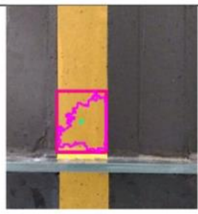
Fig. 12 AUV depth's variation against setpoint value.

The experiment results indicate that PID algorithm is successfully used for depth holding. Based on the plot of the graph in *Fig. 12*, there are variation of depth value against setpoint but within a tolerable condition. There is a deviation that varies with a fairly small range (error average 1.28 cm).

B. Line Tracking Experiment Results

The results are shown on TABLE V. When the central point (green dot) position are precisely on center of the line, the vehicle is automatically move forward following the line. If the dot position is on the right position, system will adjust the position to the left according to the setpoint. Otherwise, when the dot position is on the left, system will adjust the position to the right according to the setpoint.

TABLE V. LINE TRACKING RESULT

Video Captured	Left Motor	Right Motor	Output
	1	1	Forward

	0	1	Adjust left
	1	0	Adjust right

IV. Conclusion

This paper successfully presented an alternative method for developing AUV control system by combining smartphone-based image processing system and proximity sensor. Firstly, PID algorithm can successfully implemented as a depth holding program on AUV within 1.28 cm error average. Secondly, line tracking application can be used to control AUV's motor to adjust its position automatically.

A combination between depth controller and line tracking controller had been designed and implemented in SANDY AUV. The effect of positive buoyancy on surge, yaw, and heave dynamics is discussed and handled directly by the proposed controller scheme. Experimental results indicate that the control system is effective in controlling the depth of the AUV with negligible steady state error.

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