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Autonomous Way-Point Tracking Navigation of Surveying Surface Vessel with Real-Time Positioning System

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***Abstract*— This paper presents design and development of a long-range Autonomous Surface Vessel (ASV) for surveying water resources. This surface vessel, equipped with an echo sounder, can record and report a depth measurement in real-time for water-management purpose. This surface vessel, propelled by a 25-hp outboard engine and turned by a hydraulic steering, can be operated in either remote control or autonomous control modes. In the autonomous mode, a waypoint tracking algorithm using PID controllers adjusts heading direction to follow two-waypoint bearing as well as engine speed to ease vessel turning. Both vessel heading and position, respectively measured from IMU and GPS, are feedback signals to the waypoint-tracking controller, processed with an on-board embedded computer. Nevertheless, detecting the vessel location in vast area is a difficult task, a web application combining with Google map is implemented to report a real-time position of this surface vessel. A 3G wide-area communication is employed to transfer the data through Socket.IO using UDP for fast communication.**

Keywords—autonomous surface vessel; way-point tracking; real-time position identification; 3G communication

I. INTRODUCTION

In present day, Autonomous Surface Vessels (ASV) have been constructed in many sizes and forms for various applications; for example, bathymetry survey [6,9] and water-quality monitoring [1,4]. Main purpose of most ASVs is to replace human operator in case of surveying in hazardous areas, lacking knowledgeable personnel, and operating for a long period. Another important aspect of the survey vessel is a real-time communication that can conveniently store survey data onto a web server and can create a database during field operations. Thus, a chance of data loss is reduced and then this database could be used for further water management; such as, water-resource planning, disaster assessment in monsoon season or in oil-dispersion accident.

Bourgeois B. and *et al.* [2] from Naval Research Laboratory has developed an unmanned ASV, known as ORCA, for ocean survey applications, which can deploy different types of sensors to monitor ocean data and to store these marine data onto a database. The ORCA structure is similar to an underwater robot with a pole that can be extended up to the surface for transmitting/receiving radio signal. The ORCA uses an acoustic sensor or echo sounder for performing Bathymetry upto 300 meters and a CCD camera for transmitting live image to the surface. Autonomous navigation system of the ORCA uses GPS and Gyrocompass sensors that transmit ORCA position and orientation to the surface vessel through high-speed radio wave. This underwater communication system can cover 5-mile area and can transmit data with speed of 946 Kbit/sec

Several ASVs have been designed in a single-hull form [1,3,5,6,8] or a double-hull form [4,7,9]. The Charlie USV is a small catamaran developed by the CNR-ISSIA [1] that can be controlled by the self-oscillation line following controller. Autonomous waypoint tracking control using a state-variable feedback controller combining with observer has been implemented for a 3.85-m long kayak boat, driven by a podded propulsion [6]. At the National Taiwan Ocean University, the autopilot control of a small boat, developed by C.Y. Tzeng and *et al.* [5], uses a Real Time Kinematic (RTK) GPS-based track-keeping control, modified from the Internal Model Control (IMC) consisting of a sequence of course-changing maneuvers and a modified 4-quadrant line-of-sight guidance rule. A low-cost ASV [7] has been incooperated with INS/GPS integration using Kalman Filter for its navigation system and a look-up table controller, based on heading and distance error, for its autonomous operation.

The mobile-network telecommunication has been developed for several decades. Currently, the 3rd Generation (3G) communication provides faster communication with vast coverage area. Because of its ease accessibility and availability, 3G communication often employs in several robotics systems. For example, a biped-walking robot, developed by Rui Zhong and *et al.* [6], can be controlled and monitored by a mobile phone. An operator, controlling this

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robot, could monitor its movement via motion video. Another application for the robot control using 3G network is a humanoid robot, built by A.S. Aslam Hussaini and *et al.* [7]. This humanoid robot can detect and notify human presence and can rescue a human in disaster situation or in the battle field. This 3G communication is not only use in survey- and rescue-robotic systems, but it is also used in tele-healthcare robotic applications [8]. This tele-healthcare system using 3G communication could improve a patient monitoring service.

In this research, the architecture design and hardware construction of surveying ASV, consisting of propulsion, navigation, communication systems as well as hydrographic sensors, are introduced in section II. The guidance control design using PID controllers for tracking specified waypoints, implemented in LabVIEW, are explained in section III along with a technique for real-time vessel-position monitor. Moreover, the web application, developed for reporting ASV position in real time, is described in section IV. Then, section V demonstrates experimental results of the waypoint tracking control, depth survey data, and real-time positioning system. Finally, section VI discusses future applications of this ASV.

II. SYSTEM DESCRIPTION

Overall architecture design and construction of this surveying ASV composes of three main parts: *A)* propulsion engine, position control of hydraulic steering and engine throttling control using a gear box. *B)* ASV's navigation and hydrographic sensors, *C)* mobile-network communication. Main objective of this system design is to automate the vessel so that the vessel could be operated in either remote-control or autonomous modes as well as the operator can observe the vessel position in real time.

A. Propulsion System

A Phoenix V-shape aluminum boat with a dimension of 3.5-m length x1.52-m width x 0.6-m height is used as a based structure for constructing this ASV. This boat, as shown in Fig. 1, is made of 1.66-mm thick marine grade aluminum and it can carry maximum payload of 250 kg. A maximum engine weight that could be supported by this boat is 32 kg. The main propulsion of this ASV is a YAMAHA 2-stroke, 2-cylinder, 496 cc., 25-hp outboard engine, which has a fuel consumption of 10.7 liter/hour and equips with a CDI ignition starter that can be operated in manual /electronic control.

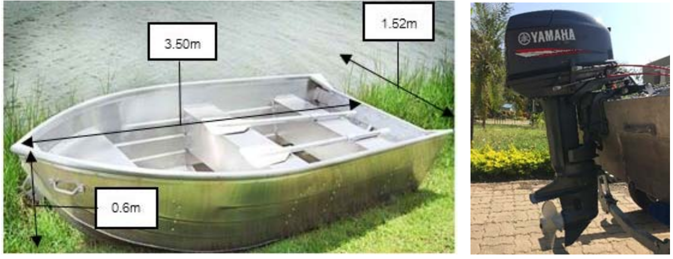

Fig. 1. V-shape aluminum boat as a based structure (Left) and Yamaha 2-stroke, 496 cc., 25-hp outboard engine (Right).

A hydraulic steering system for the outboard engine is employed a Seastar Pro cylinder and support rod, shown in Fig. 2, installed at the boat stern. Steering angle of this hydraulic cylinder is constrained between ±45°, demonstrated in Fig. 3. This steering cylinder is connected to helm through two hoses for transferring hydraulic fluid from one-side to another during turning. Thus, ASV's automatic steering system can be implemented by coupling a 12-VDC gear servo motor to a helm shaft, as shown in Fig. 4. This steering servo motor with a 500-pulse rotary encoder as a angular position feedback is controlled by an ARM7 microcontroller through a 80-A H-bridge motor driver. Using a proximity sensor installed on a left side of the hydraulic cylinder, the left-most position of this cylinder could be detected such that the outboard engine moves to the center position, set as 0 degree, after turning on the control system.

Fig. 2. A connection diagram for hydraulic steering system.

Fig. 3. Hydraulic steering cylinder for the 25-hp outboard engine installed at stern in maximum left-turn position (Left), in center position (Middle), in maximum right-turn position (Right).

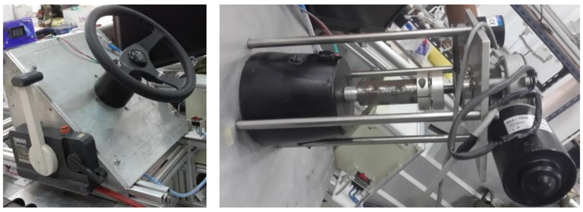

Fig. 4. Hydraulic helm with steering wheel before modification (Left); Gear DC servo motor coupled with helm's shaft after modification (Right).

A YAMAHA control 701 gear, shown in Fig. 5, is used for changing the outboard engine gear and throttling engine speed. Three control gear positions are forward, backward and neutral. To propel the vessel forward/backward, a gear lever must be moved respectively forward/backward 35° to engage the engine gear. To speed up engine either for forward- or backward-throttle, the gear lever must be pushed above 35° correspondingly in forward/backward direction. Likewise, a low-level control of gear engagement system is performed by ARM7 microcontroller to control another 12-VDC gear servo motor, coupled to the gear level's shaft, using another 80-A H-bridge motor drive with 500-pulse encoder. Three proximity sensors, installed at 0 and ±35° from the vertical axis, can verify the gear engagement and can provide a safety for the engine operations.

This ASV could be controlled in either remote-control or autonomous way-point tracking mode. In the remote control mode, ARM7 LPC2138 microcontroller receives two Pulse Width Modulation (PWM) commands for hydraulic steering and engine gear/throttle controls from a 4PK Futaba 2.4-GHz receiver, while the embedded computer directs ARM7 microcontroller to send these two PWM commands in the autonomous mode. A connection diagram for the propulsion system of YAMAHA 25-hp outboard engine is shown in Fig. 6. An electrical power source for automatic engine steering and gear controls is obtained from a 12-VDC deep-cycle lead-acid battery, which could run the propulsion system for over 4-hour period. Summarized specification of this surveying ASV is given in Table. 1.

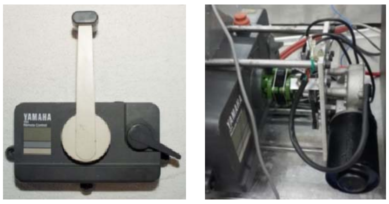

Fig. 5. YAMAHA remote control 701 gear (Left); gear-box of outboard engine connected to the gear servo motor (Right).

TABLE I. VESSEL HARDWARE SPECIFICATION

Vessel Length	3.5 m
Yamaha 2-Stroke, 496 cc, outboard engine	25 hp
Maximum Speed	~60 m/s
Operating time of fuel tank (24 Liter)	~6-8 hours
12-VDC deep-cycle lead-acid battery	135Amp/hr

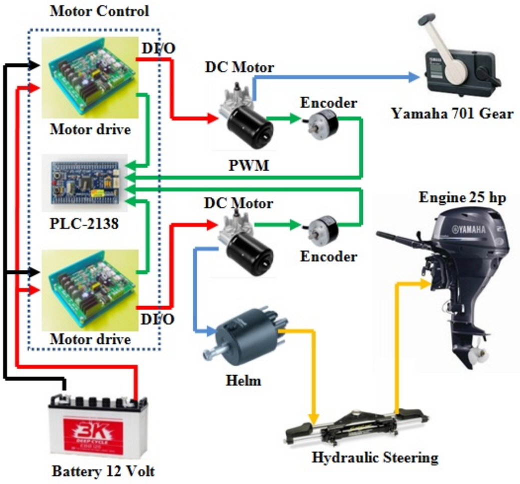

Fig. 6. The connection diagram of the vessel propulsion system.

B. *Vehicle Navigation and Hydrographical Surveying Sensors*

To track specified waypoints in the autonomous mode, navigation sensors are FlexPak 6 Novatel GPS and 3DM-GX3-45 microstrain IMU, which can provide the vessel location (Latitude/Longitude) and the vessel Euler angle, respectively. The single point L1 mode of the FlexPak 6 Novatel GPS can achieve the best horizontal positon accuracy of 1.5 meter with a maximum data rate of 100 Hz. The Euler angles, measured from the 3DM-GX3-45 microstrain IMU with a maximum sampling rate of 100 Hz, have accuracy of ±0.5° and ±2° in stationary- and maneuvering-conditions, respectively. The GPS/IMU sensors connect and send vessel position and orientation to an Advantech UNO-2184G embedded computer correspondingly through RS-232/USB ports. Both Novatel GPS and main embedded computer are installed inside an electronic box, as shown in Fig. 7, to protect against water splash. While the microstrain IMU is placed on an aluminum pole, installed at the vessel fore, to avoid electromagnetic disturbance, emitted from engine as well as from DC servo motors of the propulsion system.

To perform bathymetry survey or measure water depth, Garmin 421s echo sounder is attached to the vessel stern, as displayed in Fig. 7, and transmitted data to computer through RS-232. An electrical power source for these navigation and surveying sensors is from another 24-VDC lead-acid battery. A connection diagram of navigation and surveying sensors to computer as well as to power source is exhibited in Fig. 8. Summary of sensors' performance is described in Table. 2.

Fig. 7. Garmin 421s echo sounder at the vessel stern (Left); Advantage embedded computer and Novatel GPS inside the electronic box (Right).

TABLE II. NAVIGATION AND SURVEYING SENSOR SPECIFICATION

Horizontal position accuracy of Novatel GPS (10 Hz)	±1.5 m.
Euler angle accuracy of 3DM-GX3-45 microstrain IMU (10 Hz)	±2.0degrees
Maximum water depth measurement of Garmin 421s echo sounder	457 m.
24-VDC deep-cycle lead-acid battery	270 Amp/hr

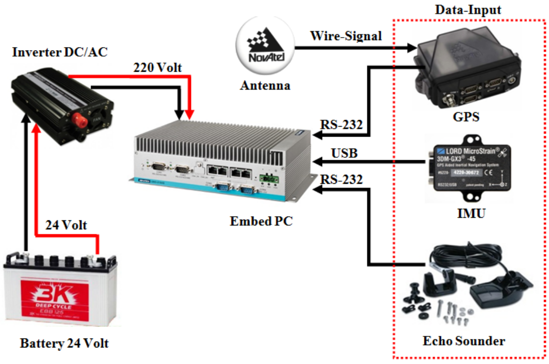

Fig. 8. The connection diagram of the vessel navigation and network communication and surveying sensor.

C. *Communicational Design*

A connection diagram of network communication devices for real-time vessel-position monitor is shown in Fig. 9. The network communication devices are comprised of a 3G NBG4115 Zyxel router along with its USB Dongle for placing a 3G SIM card from an Internet Service Provider (ISP) and a network server. This 3G router can handle service-communication tasks such as routing and forwarding package to a destination via the ISP. Measurements of vessel position and water depth are recorded on the embedded computer and real-time reported on the web application via 3G internet network. The embedded computer sends packets, containing information from these two sensors, to this 3G router.

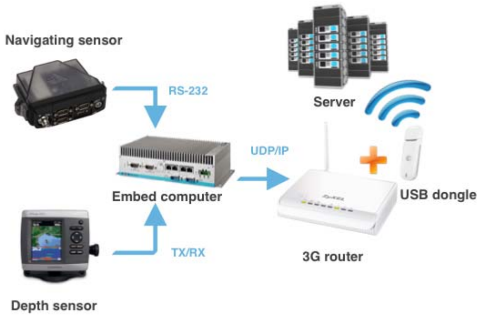

Fig. 9. A connection diagram for 3G-network communication.

III. GUIDANCE CONTROL DESIGN

The way-point tracking algorithm must be able to control the propulsion system: both engine steering and engine speed, so that the boat heading points toward the goal waypoint and a distance between boat and the goal waypoint is reduced. To deal with the vessel translational and rotational motions, reference frames must be defined for GPS using a geodetic datum, for IMU using North direction. In the autonomous mode, the vessel current heading angle (φ) and position (Lat_b, Lon_b), respectively measured from the microstrain IMU and Novatel GPS, are used to compute tracking errors for the PID controller.

Fig. 10. System integration of the surveying vessel.

First, the heading error (θ) is defined as a difference between the bearing angle (β) and the heading or yaw angle (φ) with respect to North direction, as described in Eqn. (1). The heading or yaw angle is directly measured from the microstrain IMU. The bearing angle is computed from a straight line joining between two consequence waypoints, as expressed in Eqn. (2) and illustrated in Fig. 11.

$$\theta = \beta - \varphi \tag{1}$$

$$\beta = \tan^{-1}[(Lon_2 - Lon_1)/(Lat_2 - Lat_1)] \tag{2}$$

where

(Lat_b, Lon_b) = (latitude, longitude) of the boat position
(Lat_1, Lon_1) = (latitude, longitude) of 1st waypoint
(Lat_2, Lon_2) = (latitude, longitude) of goal or 2nd waypoint

Second, the distance error (D) between current boat position and the goal waypoint is defined using the distance formulation, as shown in Eqn. (3).

$$D = \sqrt{(Lat_2 - Lat_b)^2 + (Lon_2 - Lon_b)^2} \tag{3}$$

Two PD controllers for controlling the hydraulic steering and engine throttle respectively minimize the heading error (θ) and the distance error (D) such that both errors gradually decrease to zero. The PD controller for hydraulic steering, denoted by PD_H, adjusts the vessel yaw angle such that it is parallel to the bearing angle. On the other hand, the PD controller for engine throttle, denoted by PD_E, regulates the vessel speed according to the distance error (D). Gains of these two PD controllers can be tuned separately.

$$PD_E = k_{p1} D + k_{d1} (dD/dt) \tag{4}$$

$$PD_H = k_{p2} D + k_{d2} (d\theta/dt) \tag{5}$$

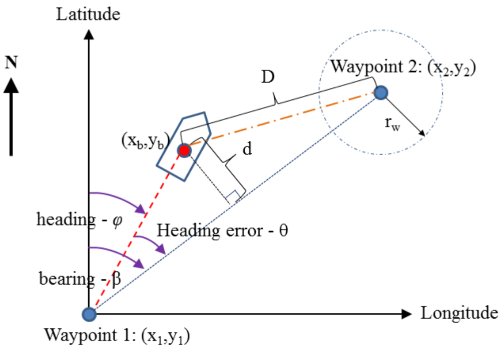

Fig. 11. Definitions of the heading error and distance error for two PD controllers.

IV. REAL-TIME POSITION TRACKING OF AUTONOMOUS VESSEL

In real environment, an autonomous surface vessel may faces with various problems such as fishing-net or aquatic weeds obstruction, GPS signal lost, magnetic compass error, and etc. These problems may disrupt the vessel operation for a few minute or can even lead to breakdown with longer downtime. If these problems occur during the autonomous mode near shore, discontinuity of surveying operation could be resolved immediately. However, in large-area survey area, the boat location is very difficult or impossible to identify because of limited visibility. Therefore, the boat position becomes valuable information for the operator to track the boat whereabouts, to detect the operation disruption instantaneously, and to reduce a risk of boat lost or severe damage.

A. Real-Time Communication

To report the position of this autonomous vessel from anywhere in the surveying site, a real-time position tracking system is developed as a user supporting system. The main objective of this tracking system is to inform the operator about the geodetic data and depth of the surveying environment onto a Google map service in real-time. Three main components of a real-time report system are communication service, real-time communication engine and a transmission protocol. A 3G wide-area wireless service is employed as a main communication service. A 3G transmission speed of the information packets is fast enough to identification the boat real-time position.

Socket.IO is a real-time event-based communication engine of Javascript. This engine provides several useful communication functions which are able to call by a web browser supported programming language, like Javascript. A transmission protocol is a User Datagram Protocol (UDP) that is a non-handshaking protocol. Furthermore, UDP does not necessary to set up prior transmission channels and to wait for slow acknowledgment as the other types of handshaking protocols. As a consequence, a fast transmission could be achieved. However, the ordering of receiving packets is not guaranteed, but this unordered data is relatively easy to check and to filter out. After software is executed and connected to internet, all geodetic data and depth information are encapsulated in UDP packets and sent these information to server destination address and server listening port. Later, these packets emit an incoming message event back to the Socket.IO engine. Then, received data can be used by other programs, like Google map service.

B. *Web Application Development*

Not only, this software reports the geodetic data and depth in text format, but it also illustrates the geodetic data on the Google map as a real-time moving coordinate using web programming languages, such as HTML and Javascript. Google map API is written to directly interface with Javascript language. This API provides a set of map objects and methods that many object provided by Google map service could be customized. The process of this web application, shown in Fig. 12, is described below.

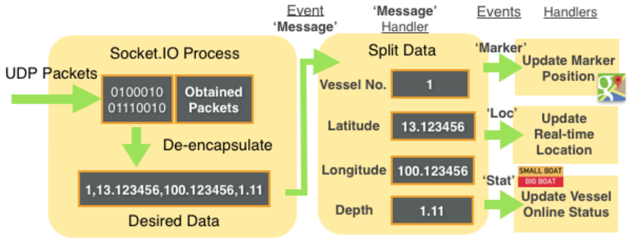

Fig. 12. The procedure of real-time report system on a server side.

First, this application begins with sending the measured data from the Socket.IO engine, then these data are organized in predefined format. These data could extract the numerical alphabets from NMEA-format alphabets that describe geodetic coordinate, depth, and the vessel number. Then, these three data sets are reported on the web application in a form of text, and the HTML element. As a result, the vessel location is online reported on this web application in numerical format. Second, the Google map API generates a positioning marker from the geodetic coordinate using a marker function to update this marker position every second. Therefore, this marker acts as an agent of this surface vessel, updated in real time. In additions, the real-time vessel path, called from the Google map API, can be illustrated for any users, logging into this web application.

V. AUTONOMOUS WAY-POINT TRACKING EXPERIMENTS

This section shows two different experiments of waypoint tracking control with challenging paths: 1) 4-waypoint square path, and 2) 5-waypoint M-shape path. Furthermore, both 2D and 3D trajectories can be visualized from the RMUTT-pond survey data. Also, results of real-time positioning report are given for these two experiments.

The first experiment with 4 waypoints demonstrates a turning-performance of the hydraulic steering control using two PD controllers. These 4 waypoints forming a square with sharp turns, which is difficult for the trajectory tracking control, could test the turning performance of the vessel hydraulic steering. The vessel trajectory in the autonomous control mode for 3 rounds are shown in Fig. 13, this result reveals that the vessel can make sharp turns very well and all 3-round trajectories in a counter-clockwise direction are closely matched. Similarly, the vessel heading is adjusted to travel along the straight line by the PD controllers with $k_p = 15$ and $k_d = 21$ respectively.

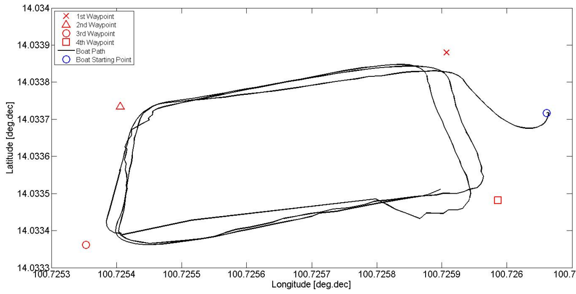

Fig. 13. Three-round trajectory of Autonomous Waypoint Control for 4 specified waypoints with waypoint radius of 1.0 meter.

In the second experiment, 5 specified waypoints form a M-shape path. This experiment establishes even more difficult autonomous tracking trajectory, the vessel has to make two 160-deg turn in each round. The result of this autonomous tracking mode using the PD control gains of $k_p = 15$ and $k_d = 21$ with waypoints radius of 1 meter is shown in Fig. 14. Nevertheless, the vessel, operated in the autonomous control mode, can precisely track the same straight paths, joining each pair of waypoints, in all 3 rounds.

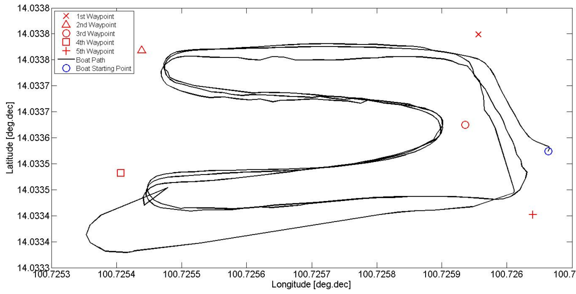

Fig. 14. Three-round trajectory of Autonomous Waypoint Control for 5 specified waypoints with waypoint radius of 1.0 meter.

Furthermore, Fig. 15 demonstrates a 3-D visualization of the survey data: latitude/longitude/depth of the second experiment, in the RMUTT pond. The depth information is measured by the echo sounder with a sampling rate of 1Hz. Likewise, depth data in each round along the M-shape path closely overlays each other. This 3-D visualization from this autonomous waypoints tracking trajectory could help roughly estimating a volume of the RMUTT pond.

For a real-time position tracking system using the web application development in section IV, the results from the second experiment with 4 waypoints and third experiment with 5 waypoints are shown in Fig. 16. The geodetic coordinate and depth information in text format are updated every second in the top-right textbox. Besides that, the vessel position is represented by a red drop pin at each instance and the boat trajectory is drawn as a continuous red line on the Google map service. As a result, this real-time positioning system could help the operator to track the boat position instantaneously in case that there is any unexpected problem to stop the vessel during the autonomous-mode control, the operator could detect this incident and easily pinpoint the vessel location to prepare for a rescue operation. Furthermore, using the 3G-network communication, several users could access this real-time positioning system of the autonomous boat from any devices that can access the internet as well.

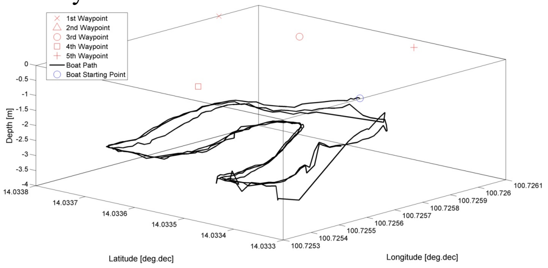

Fig. 15. The vessel trajectory and surveyed depth in 3D from five-waypoint tracking test in RMUTT pond.

Fig. 16. Web application development for online vessel positioning report of the 2nd experiment (Left) and 3rd (Right) experiment.

VI. CONCLUSION

In this research, the autonomous surfaces vessel has been designed and constructed for surveying water resources, and the real-time positioning system through 3G communication is also developed with the UDP protocol and the web application development as a mean for the operator to monitor the vessel operation in vast survey area instantaneously and to detect any unexpected problem. For the main propulsion and steering system, the 25-hp outboard engine and hydraulic steering are installed along with motorized systems for remote- or computer-control purposes. Furthermore, GPS and IMU are employed as the navigation sensors for feeding back the vessel location and heading angle to two PD controllers. In the autonomous mode, the first PD control adjusts the hydraulic steering so that the boat heading to align with the straight line between two consecutive waypoints. The second PD control varies the engine throttle to change the vessel speed according to the distance between the current boat position and the goal waypoint. For the real-time positioning system, the boat geodetic coordinate and depth information display in both text and graphical format on the Google map service.

The autonomous waypoint tracking results reveal that this surface vessel can precisely track different path types very well. Also, the constructed propulsion system provided well turning and maneuvering performance. The real-time positioning system through 3G network can updated the boat location promptly, which is very convenient for the operator to track the boat movement, especially in the autonomous mode, and to detect any problem suddenly. All latitude, longitude, depth information could be used for bathymetry application.

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