Preprints of the 19th World Congress
The International Federation of Automatic Control
Cape Town, South Africa. August 24-29, 2014

Development of an Unmanned Surface Vehicle Platform for Autonomous Navigation in Paddy Field

Yufei Liu*. Noboru Noguchi.**
Takeshi Yusa***

**Graduate School of Agriculture, Hokkaido University, Kita-9, Kita-ku, Sapporo, Hokkaido 060-8589 Japan (e-mail: liu@bpe.agr.hokudai.ac.jp).*

***Research Faculty of Agriculture, Hokkaido University, Kita-9, Kita-ku, Sapporo, Hokkaido 060-8589 Japan (Tel: +81.11.706.3847; e-mail: Noguchi@ bpe.agr.hokudai.ac.jp).*

****Graduate School of Agriculture, Hokkaido University, Kita-9, Kita-ku, Sapporo, Hokkaido 060-8589 Japan (e-mail: Yusa@bpe.agr.hokudai.ac.jp).*

Abstract: The objective of this research was to develop an unmanned surface vehicle (USV) platform for autonomous navigation in the paddy field. The surface vehicle used in this research was a radio controlled air propeller vessel that had been modified into an unmanned surface vehicle platform. A GPS compass system was attached to the top of the USV platform as the navigation system to provide the position and heading angle. The USV platform can autonomously navigate to the predefined navigation map. From the GPS trajectory data of the map-based navigation experiment, the in-system root mean square (RMS) lateral error from the target path was observed to be less than 0.45 m, and the in-system RMS heading error was 4.4 degree or less. The final goal of the research is going to realize the autonomous weeding, intelligent fertilization or paddy growth management based on this USV platform.

Keywords: Unmanned surface vehicle; Autonomous navigation; GPS compass; Paddy field.

1. INTRODUCTION

In developed countries, the population and aging problems of agriculture practitioners is serious year by year. Thus, the development of the automated machine for farming work is more and more important. Paddy as the main food crops, is widely planted. During the period of paddy planting, some farming work should be implemented, including paddy seedlings cultivation, field tillage, paddy transplant, spaying, mechanical weeding, fertilization and paddy harvesting. For each part, the development of automation is meaningful. In the past, as described in previous reports, many research achievements were published. Noguchi et al.(2002) developed a field robot in agricultural operation environment with a real time kinematic global positioning system (RTK-GPS) and an inertial measurement unit (IMU) as navigation sensor to do tillage, planting and cultivating. Nagasaka *et al.*(2004) developed an automated rice transplanter with autonomous guidance operation. The root mean square deviation from the desired straight path was approximate 5.5 cm at a speed of 0.7 m/s. Kim *et al.*(2012) developed a robot platform which can do weeding while traveling between rice seedlings stably against irregular land surface of a paddy field. Coen *et al.*(2008) designed a robust automatic guidance system for a combine harvester. The automatic steering system controls the harvester based on the measured position of the swath on the field. The swath is detected by using a laser scanner.

In addition, the unmanned surface vehicles are vehicles that operate on the surface of the water without a crew for data acquisition. Because of the flexible, cheap and capable features, various unmanned surface vehicles have been developed and applied in many science and technology fields like geophysical exploration and environmental monitoring. Kaizu *et al.*(2011) developed an unmanned airboat that automatically navigated to predefined sampling points, measured specific water quality such as pH, and dissolved oxygen and electrical conductivity in the mire pool. Subramanian *et al.*(2006) designed an autonomous surface vehicle for shoreline detection in images. There was an on board GPS and a wireless ethernet remote operation system fixed on the surface vehicle. A single omnidirectional camera is mounted in the front of the surface vehicle to assist in navigation. The images from the omnidirectional camera provide a 360 degree view of the entire scene. David *et al.*(2007) designed an autonomous surface vehicle, named IRIS, to survey pre-programmed track lines for creating geophysical map of Oyster habitats in Apalachicola Bay, Florida, USA.

Paddy crop is a semi-aquatic plant. It is strongly influenced by water supply. Water should be kept standing in the field throughout the growth period. In the long period of paddy growth, the paddy filed is submerged in about 5-10 cm depth of water. So, above these characteristics, it is suitable to develop an unmanned surface vehicle platform running in the paddy field to do some farming work. Because the surface vehicle floats on the water, the paddy crops will not be crushed. This is a cheaper and more flexible automatic research project.

The main objective of this study was to develop an agricultural unmanned surface vehicle platform, which can autonomously navigate to the predefined navigation map under the farming working requirement.

2. MATERIALS AND METHODS

The following descriptions are the main hardware components of the USV platform and the navigation method implementation based on this USV platform.

2.1 Platform Hardware Description

The environment characteristic of the paddy field should be considered in the design idea. For example, the USV platform should be light enough to float on the water, and can control steering easily. Besides, the cost of this USV platform should be kept down to a minimum on the condition that the acceptable navigation precision is guaranteed. As mentioned above, the paddy field is submerged, but the water is not more than 10 cm deep. So, the underwater propeller surface vehicle cannot be used and it is pivotal to choose an applicable surface vehicle body. Fig. 1 shows the USV platform. In this study, a radio controlled air propeller vessel (RB-26, Hokuto Yanmar Co., Ltd., Ebetsu, Japan) was modified to the main body. The draft of the surface vehicle is 5 cm in full load.

Fig. 1 Unmanned surface vehicle platform

For autonomous navigation, a computer (DN2800MT, Intel Corporation, USA), running Windows 7 operation system, was used on the USV platform. The computer was responsible for navigation planning, communicating with other electronic devices and saving the running state data. A GPS compass system (V100, Hemisphere GPS, Calgary, Alberta, Canada) provided position and heading angle information. The precision of the position was less 1.0 m RMS and the precision of the heading angle was about RMS 0.5 degree. In order to control the heading of the USV, an electronic control unit (ECU) based on an Arduino (Arduino UNO, Arduino LLC) on-board computer system was manufactured and used to be the core of underlying devices communication.

Fig. 2 shows the block diagram of the USV platform hardware. The hardware system was divided into two parts. One part was on the shore of paddy field. The laptop which received the wireless signal from USV platform via the wireless router was used to monitor the running state of the USV platform such as speed, heading, and position. The radio controller with 8 signal channels, operated by manual, can control the USV platform. In case of emergency, pushing the remote emergency button system (WT-01 & WR-01, Circuit Design, Inc., Japan) can turn off the engine of the surface vehicle. The other part of the hardware system was on the surface vehicle. There were three servo motors, respectively connecting the throttle of the engine to control the engine power, the air propeller to change the fan's pitch angle and the rudder of the surface vehicle to control the heading angle. The magnetic sensor (GV-101, FUTABA Corporation, Japan) was attached to the outside of the engine shell which was the rotor to measure the rotation speed of the engine. It, as the feedback data, was used for controlling the rotation speed via PID control. The GPS compass system was connected to the PC by serial port to collect the navigation data. The PC also calculated the navigation path planning and sent command messages to the ECU to control the three servo motors to renew the running state of the USV platform.

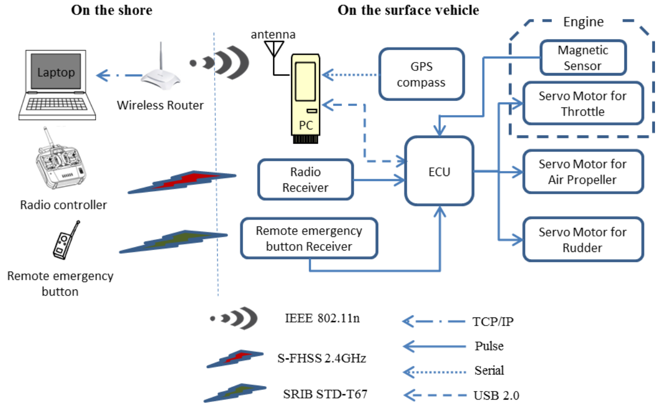


Fig. 2 Block diagram of the USV platform hardware

2.2 Navigation Control Method

For the surface vehicle, because of the disturbance of the wind, wave and flow, the vehicle motion is regarded as a six degree of freedom (6-DOF) rigid body motion in space as shown in Fig. 3. According to the naming system from the society of naval architects & marine engineers (SNAME), the three translational motions are surge, sway and heave. The three rotational motions are roll, pitch and yaw.

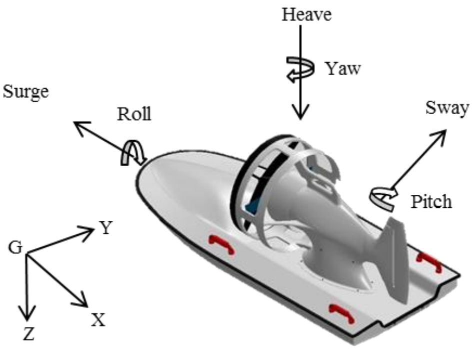


Fig. 3 The 6-DOF motion of the USV platform in geodetic coordinate system

However, for surface vehicle motion study, because the water is shallow in paddy field, in normal conditions, the depth of water is not more than 10 cm. Meanwhile, except irrigation time, the water flow effect can be neglected. Hence, for the sake discussion convenience, the motions of vehicle in heave direction, pitch direction and roll direction can be tolerably ignored. So, it is treated as a horizontal motion control, which means just surge, sway and yaw, 3-DOF are considered.

Almost all the farming work should be done in every area of the paddy field. In addition, the paddy is planted not disorderly and unsystematic, but row by row, which is beneficial to the management and harvest. Therefore, the USV platform navigation should run along the paddy row and traverse whole the paddy field. The desired path map was planned based on the actual environment and the operation requirement of farm work, and this should be done before the autonomous navigation. The path mapping parameters included navigation beginning point and end point, path space and the number of paths. Sending these parameters to the on-board computer of the USV platform can generate navigation map automatically.

From the navigation map, the path consists of straight line vectors and turnings at every end of the straight line. So the autonomous navigation also can be divided into two parts as follows:

- Line-following navigation
- Turning control

When the USV platform ran in the paddy field, it will deviate from the desired line due to the disturbance of wind. Fig. 4 shows the pictorial representation of the line-following navigation of the USV platform.

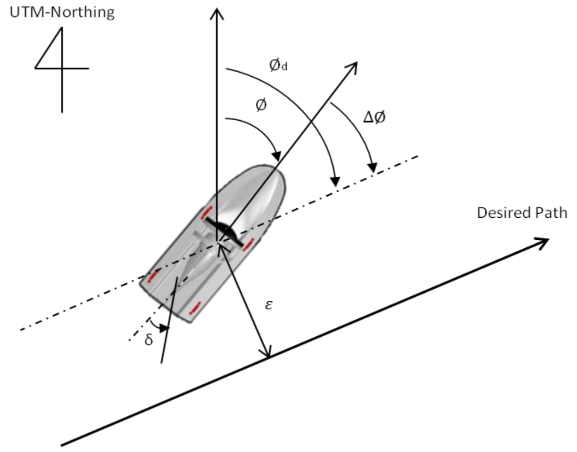


Fig. 4 Line-following navigation of the USV platform

The change of motion state was limited by the rudder steering angle given by (1).

$$\delta = f_1(\varepsilon_t) + f_2(\Delta\phi_t) \quad (1)$$

where δ is the rudder steering angle. It is calculated by two functions. The $f_1(\varepsilon_t)$ is the function related to lateral error ε_t from the USV position to the desired line given by (2). The $f_2(\Delta\varphi_t)$ is the function related to heading error $\Delta\varphi_t$ given by (3), which relative angle is between the desired heading φ_d and the USV real-time heading φ measured by GPS compass. Subscript t denotes the present moment.

$$f_1(\varepsilon_t) = K_1 \cdot \varepsilon_t + K_2 \cdot (\varepsilon_t - \varepsilon_{t-1}) \quad (2)$$

$$f_2(\Delta\phi_t) = K_p \cdot \Delta\phi_t \quad (3)$$

where K_1 and K_2 are the proportion gains for lateral error in the present time t and the previous time $t-1$. And K_p is the proportion gain for heading error. Proportion gains of K_1, K_2 and K_p were obtained experimentally.

In the autonomous navigation control, after line-following navigation, the USV platform should turn around at the end waypoint position to enter the subsequent path. In order to adapt to the agricultural production, the navigation map is normally designed as parallel paths. Obviously, the heading of the USV platform should rotate 180 degree when doing turning.

At the present stage, a simple turning control method was used. In this research, the rudder maximum turning degree was setting 40 degree and servo motor which connected to the air propeller was kept into 120 degree with turning. The real time heading angle, which was obtained by the GPS compass, was compared with the new desired heading angle. If the heading error is less than 20 degree, the turning control should be stopped. Because of inertia, the USV platform will continue steering. At the same time, the new line-following navigation control was started to carry out in subsequent path.

Based on line-following navigation control and turning control, the USV platform can navigate continually till navigation is finished.

3. RESULTS AND DISCUSSION

According to the above control theoretical analysis, a series of autonomous navigation control experiments was conducted using this USV platform. The experiments site was chosen in the experimental paddy field of Hokkaido University, Sapporo, Japan, as shown in Fig. 5. And the navigation experiments were divided into three parts as follows:

- Line-following navigation experiment
- Turning experiment
- Map navigation experiment

Fig. 5 Experimental paddy field

3.1 *Line-following navigation*

The line-following navigation is the main part of the autonomous navigation. The goal is to minimize both the lateral error and heading error to follow the target path. Fig. 6 shows the trajectory of line-following navigation in the universal transverse Mercator projection (UTM) coordinated system. The blue line is the desired path. The red line is the line-following travelled trajectory of the USV platform in real time.

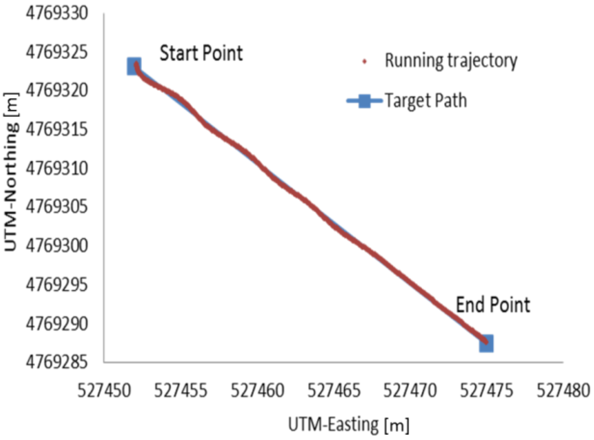


Fig. 6 Trajectory of the line-following navigation

The PC in the USV platform dynamically logged the lateral error and heading error when running line-following navigation. Fig. 7 shows the lateral error and Fig. 8 shows the heading error.

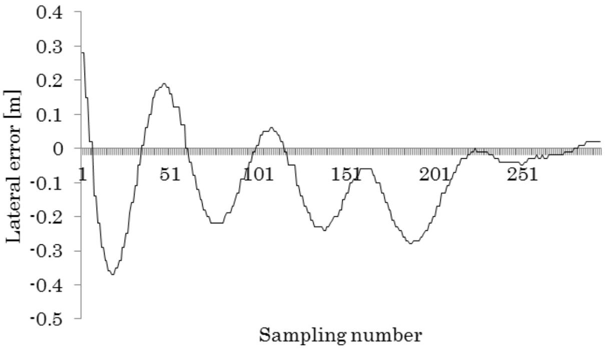


Fig. 7 Lateral error of the line-following navigation

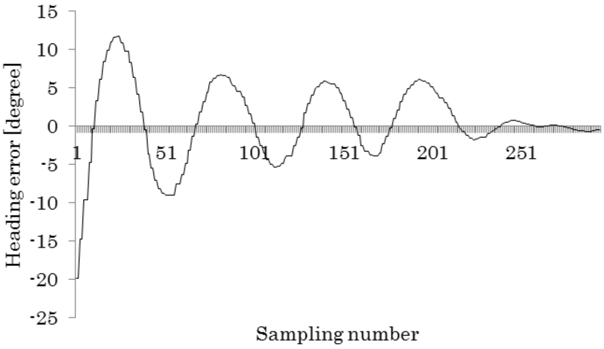
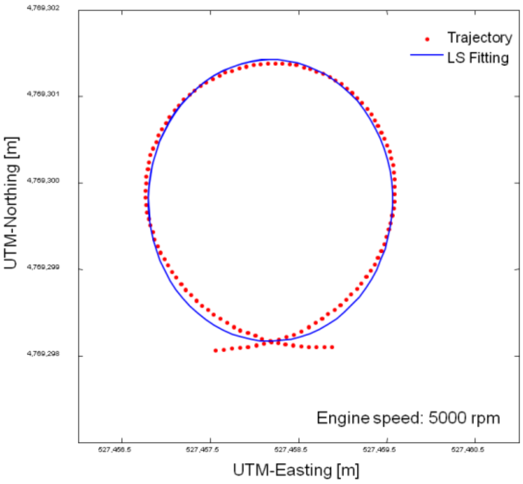


Fig. 8 Heading error of the line-following navigation

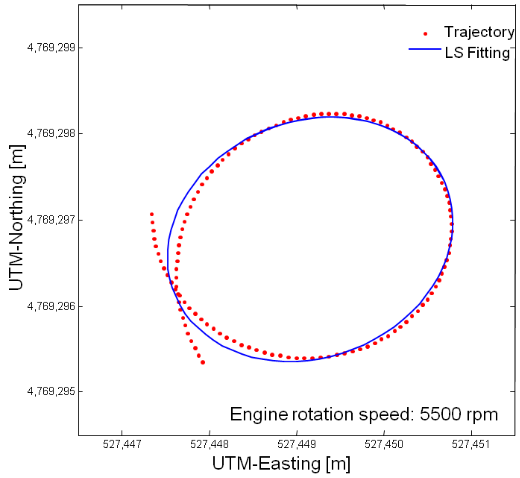
Calculated by mathematical statistics, respectively, the in-system RMS lateral error is 0.13 m and the in-system RMS heading error is 5.0 degree. From Fig. 7 and Fig. 8, they show that the larger lateral error and bigger heading error appeared at the beginning time of navigation. The reason is that the difference is big between the initial state of the USV platform and target navigation state in position and heading parameters.

3.2 *Turning*

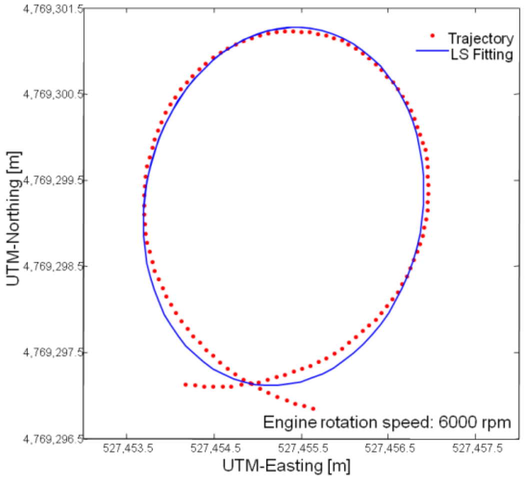
For the purpose of observing the turning performance of this USV, Fig. 9 shows the trajectory of turning test in UTM coordinated system with 4 different engine rotation speeds, 5000 rpm, 5500 rpm, 6000 rpm and 6500 rpm respectively. Under ideal situation, the trajectory of turning should be a circle. Nevertheless, the trajectory cannot be a circle, but an ellipse, that because of the influence of wind. The red waypoint is the trajectory data from the GPS compass. The blue line was the ellipse fitted using LSM (Least Square Method). Table 1 shows the major axis and minor axis of each fitting ellipse. Because the inertia motion exist in the USV platform running on water surface, the turning radius was reduced with engine rotation speed decreasing when the rudder angle steering remained unchanged.



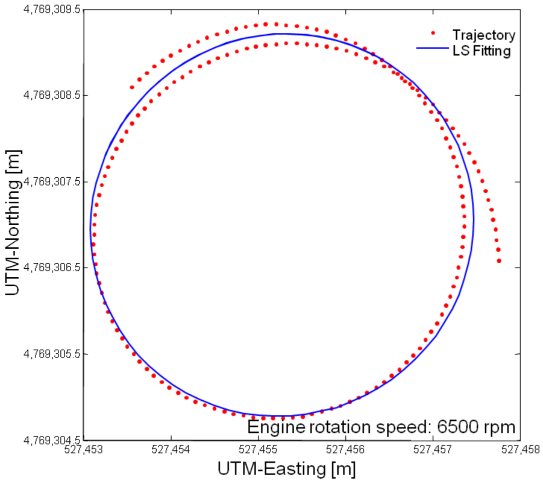
(a)



(b)



(c)



(d)

Fig. 9 Performance of turning. (a) Under 5000 rpm rotation speed; (b) Under 5500 rpm rotation speed; (c) Under 6000 rpm rotation speed; (d) Under 6500 rpm rotation speed

Table 1. Summary of the turning performance

	Engine Rotation Speed			
	5000 rpm	5500 rpm	6000 rpm	6500 rpm
Major axis	1.63 m	1.68 m	2.09 m	2.24 m
Minor axis	1.38 m	1.37 m	1.59 m	2.18 m

3.3 Map-based navigation

The map-based navigation is the combination of the line-following navigation and turning control. Some farming work can be done based on the map-based navigation.

In this experiment test, the USV platform ran around a “snake-shaped” navigation map. The navigation map was generated into five paths. The path space was 5 meters, and the UTM position of the start point A in first path was (527451.9714, 4769323.095) and the UTM position of the end point B was (527474.966, 4769287.534). Fig. 10 shows the trajectory of the map-based navigation.

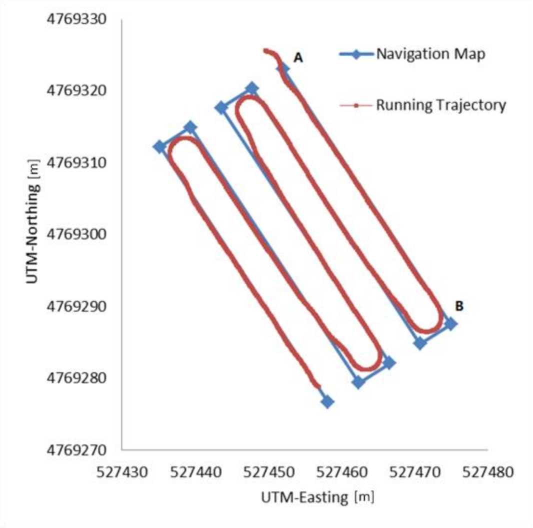


Fig. 10 Trajectory of map-based navigation

In autonomous map navigation, the USV platform ran line-following navigation from point A, then, run turning control to the subsequent path. It was circularly executed until finishing all the 5 desired paths. Fig. 11 shows the lateral error and Fig. 12 shows the heading error. Turning control method is easy, but cannot accurately control the turning radius. So, it brings in the big initial lateral error at the beginning of each navigation path. For this case, it needs more thinking and should be improved. Here, it can provide reference for the high precision turning control.

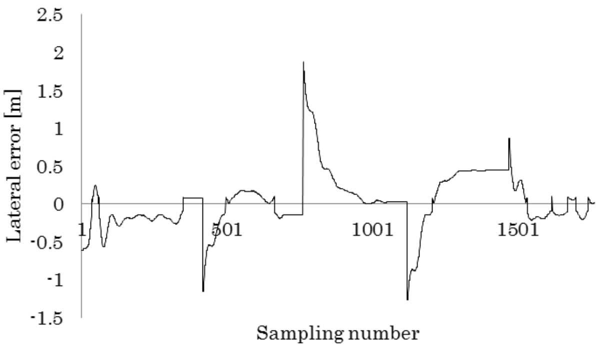


Fig. 11 Lateral error of map navigation

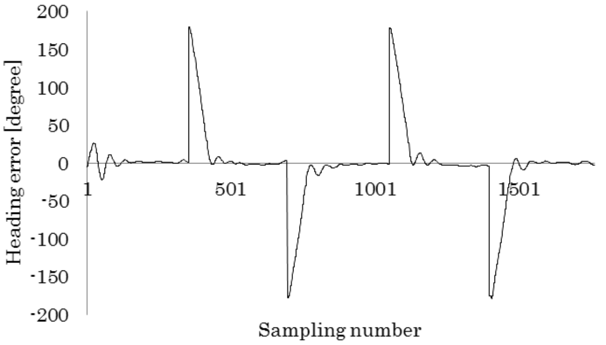


Fig. 12 Heading error of map navigation

Table 2. shows the summary of the navigation error after the USV platform running stable in each target path. The in-system RMS lateral error from the target path was observed to be less than 0.45 m, and the in-system RMS heading error was 4.4 degree or less. The in-system mean lateral error from the target path was found to be no larger than 0.22 m, and the in-system mean heading error was no larger than 3.1 degree.

Table 2. Summary of the map-based navigation error

Path No.	*Lateral Error (m)*		*Heading Error(degree)*	
	Mean	*RMS*	*Mean*	*RMS*
1	*-0.22*	*0.10*	*1.6*	*2.6*
2	*-0.07*	*0.26*	*0.1*	*2.8*
3	*0.22*	*0.22*	*-3.1*	*3.2*
4	*0.10*	*0.45*	*-1.0*	*4.4*
5	*-0.10*	*0.10*	*0.0*	*2.0*

4. CONCLUSIONS

An agricultural unmanned surface vehicle platform was developed to implement autonomous navigation in the paddy filed. This USV platform can generate automatically a high-resolution guidance map under the farming work requirement and navigate by itself to the predefined navigation map. A simple mathematical model which is appropriate for uncomplicated paddy field environment was used in the experiments. From the GPS trajectory data of 5 paths autonomous map-based navigation experiment, the in-system RMS lateral error from the target path was observed to be less than 0.45 m, and the in-system RMS heading error was 4.4 degree or less. The precision of the navigation is deemed acceptable.

About the present and future research, the USV platform can be developed more flexible and precise for control. In order to provide the autonomous weeding, intelligent fertilization or paddy growth management, the USV platform can be applied optimally.

REFERENCES

Coen, T., Vanrenterghem, A., Saeys, W., & DeBaerdemaeker, J. (2008). Autopilot for a combine harvester. Computers and Electronics in Agriculture,63, 57 ‐ 64.

David, C., Twichell, B. D., Andrews, H., Edmiston, L., &Stevenson, W. R. (2007). Geophysical mapping of oyster habitats in a shallow estuary; Apalachicola Bay, Florida. U.S. Geologicaln Survey Open-File Report, 2006-1381.

Kim Gook-Hwan, Sang-Cheol Kim, Young-Ki Hong, Kil-Su Han, Soon-Geul Lee, (2012). A robot platform for unmanned weeding in a paddy field using sensor fusion. 8th IEEE International Conference on Automation Science and Engineering. August 20-24, 2012, Seoul, Korea. p.904-907.

Kaizu, Y., Iio, M., Yamada, H., Noguchi, N., (2011). Development of unmanned airboat for water-quality mapping. Biosystems Engineering, 109(4), 338 ‐ 347.

Nagasaka, Y., N. Umeda, Y. Kanetai, K. Tanikawi, and Y. Sasaki, (2004). Automated rice transplanter using global positioning and gyroscopes. Computers and Electronics in Agric. 43(3):223 ‐ 234.

Noguchi N, Kise M, Ishii K, Terao H, (2002). Field automation using robot tractor. In: Proceedings of Conference on Automation Technology for Off-Road Equipment, ASAE, Chicago, IL. p. 239－245.

Subramanian, A., Xiaojin Gong , Wyatt, C.L., Stilwell, D,(2006). Shoreline Detection in Images for Autonomous Boat Navigation. Signals, Systems and Computers, 2006. ACSSC '06. Fortieth Asilomar Conference, Pacific Grove, CA,USA. Oct. 29 2006-Nov. 1. p: 999 – 1003.