| 類型     | 自動航海機器人バスケットの農業用機器を例として、田園の自動操縦システムに関する研究。
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| 調査項目 | 自動操縦システムの開発と応用に関する研究。                                                                                                     |
| 月     | 2017年3月23日                                                                                                                              |
| 文件類型 | これらの博士論文全文の閲覧方法については、以下のサイトをご参照ください。  
https://www.lib.hokudai.ac.jp/dissertations/copy-guides/    |
| 文件名   | Liu_Yufei_summary.pdf                                                                                                                     |

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Introduction

Human civilization has experienced the Stone Age, Agricultural Age and Industrial Age, and now it is in the Information Age. With the change of ages, the population never stops its growing. The Food and Agriculture Organization (FAO) of the United Nations (UN) predicted that people whom inhabits the planet is estimated to reach 9.15 billion by 2050. That means the food production must increase 70% by 2050. Beyond this, the humans also have to face the climate change, the water shortage, the aging problem and the lack of the arable lands bring the adverse impacts for the agricultural production. All these things are the unprecedented challenges for the sustainable development of human society.

With the development of information technology and electronic technology, the agriculture industry is embarking upon a new revolution. To solve the adverse impacts for production, represented by the climate change and the aging problem of population, and increase the quality and quantity of agricultural production, the new science and technology are implemented in the agricultural production to make the farms intelligent.
more and more. “Smart agriculture” was proposed in current agricultural revolution also known as precision agriculture (PA).

The developing smart agriculture is an agricultural revolution to change the mode of agricultural production, and then change the life-style of humans. The agricultural intelligent equipment were invented to replace human beings in doing the repeated and heavy farm work. In this case, the two serious issues, the shortage of agricultural labor force and aging problem, can be solved well based on the smart agriculture. In particular, using the sensor technology, the agricultural robot as the representative application include the robot tractors, robot transplanters, robot harvesters and so on. Many farm tasks could be carried out automatically under the autonomous navigation method. However, because of the environmental particularity in paddy field, it is hard to drive a ground vehicle such as a tractor after transplanting the paddy seedlings. But, an airboat is flexible to float on the water surface and cannot destroy the paddy seedlings. Based on the mention above, this dissertation attempted and developed the different autonomous navigation systems and methods on an unmanned airboat in the paddy field.

In order to realize the objective, several sub-goals were completed in this research. Firstly, a remote controlled airboat was modified into an unmanned airboat platform. A developed ECU and an on-board computer were set up in the body of the airboat. The remote emergency stop devices were used on the airboat for safety. A small-sized, low-cost attitude measurement unit was developed to estimate the attitude of the airboat. Secondly, for identifying the maneuverability of the airboat, zig-zag experiments were conducted based on Nomoto model to calculate the maneuverability indices. Thirdly, two path planning methods were presented. Through determine the
position of first path, the path number, turning direction and path spacing, the normal method can make a suitable path map in a rectangular paddy field. Another improved path planning method utilized the wind direction as an input parameter to make path map in any convex quadrangle paddy fields. Finally, developed and discussed the different autonomous navigation systems for the unmanned airboat application based on different sensors which were a GPS compass, a developed UAV and a laser scanner, respectively.

2 Research Platform and Platform Attitude Estimation

Because of the water depth in paddy field is less than 10 cm, the selected airboat should be light enough to float on the water surface, and with low draft, cannot damage the paddy seedlings. An agricultural radio-controlled unmanned airboat named Hokuto Yanmar RB-26 was selected in this research. This airboat was developed to do fertilizing and weeding before the middle stage of paddy growth. One liquid herbicide tank is in the body of the airboat. The herbicide can be sprayed into the water through the port of pipe at the bottom of the airboat. The maximum design environment wind velocity is 7 m/s.

This unmanned airboat was modified into the ECU and computer control. Three digital servo motors linked the engine throttle, the blade of the air propellers and the rudder, respectively. Through control the servo motors via PWM signals by using ECU, the airboat can accomplish speed change, steering orientation, running forward or backward and other status. For people, airboat-self and environment safety, three emergency stop devices were developed which included an airboat body switch button, a remote controller switch button and a Bluetooth transmitter switch button. Switch off
any one can directly shut down the engine of the airboat to avoid an accident consequently.

For estimating the attitude information of the airboat in paddy field, a small-size, light-weight and low-cost attitude measurement unit was composed out for airboat application. Because of the high-pass characteristics of gyroscope and low-pass characteristics of accelerometer, the complementary filter can combine the advantages from the both sensors. The Kalman is another popular filter which is used on data fusion processing. In order to prevent the high frequency measured noise on the gyroscope, the mean filter is used to eliminate the outlier signal as a pre-process of the angular rate obtained by the gyroscope in this low-cost IMU. In this study, a self-adaptive complementary filter and a Kalman filter were applied and compared.

In order to verify the validity of the sensor fusion methods that combines the accelerometer and the gyroscope, which are better than that of using each sensor alone, two indexes of the sensors were chosen to evaluate performance. One was the drift error and the other was the dynamic attitude angle. When the self-adaptive complementary filter and Kalman filter were used, drift was almost zero and was smoother than the data from the accelerometer. Similar to the above evaluation steps of drift error, the dynamic attitude angle data was logged when rotating the attitude measurement unit in different rotation directions. The drift errors are 1.8 degrees in the roll direction and 5.7 degrees in the pitch direction. Otherwise, the dynamic curve which was estimated by the self-adaptive complementary filter was better than the performance of each sensor alone.

In the comparison with a highly precise FOG, the drift of attitude measurement unit is same as the performance of the FOG. In addition, refer to the FOG, the RMS of
dynamic angle errors are 0.3 degrees in the roll direction and 0.4 degrees in the pitch direction. This is an acceptable measurement accuracy for automatic control in this research.

3 Mathematical Model

Modeling and control are two crucial parts for implementing the unmanned airboat automation. Furthermore, modeling is the basis of precise automatic control of heading-keeping and course-keeping. The airboat maneuverability is defined as the dynamic performance required to keep or change the airboat speed, heading and position under certain force. To describe the maneuverability, a mechanical model is used, which follows Newton’s law of motion. Nomoto model describes the dynamic relationship between the rudder deflection and the airboat turning angular rate. In contrast to other motion models, the Nomoto model is a simple structure to directly respond to the rudder effect. It gives a meaningful way to improve the control accuracy of the unmanned airboat.

To achieve precise automatic control, the maneuverability of the airboat was derived based on the Nomoto model which describes the dynamic relationship between the rudder deflection and the airboat turning angular rate. A high accuracy IMU was used for obtaining the airboat running situation. A series of zig-zag maneuvering experiments were conducted for obtaining the maneuverability indices in the paddy field of Hokkaido University campus. Then, using the obtained maneuverability indices combined with the Nomoto model to simulate the circular turning motion and sinusoidal running motion. The corresponding field tests verified the feasibility of the achieved
maneuverability indices. Results of the comparison showed the difference of turning radius between field test and simulation were 0.25 m, 0.44 m and 0.04 m in the rudder angles of 15°, 25° and 35°, respectively.

Computer simulation and corresponding field experiments verified the feasibility of the achieved maneuverability indices $K$ and $T$. The comparison of the result shows that the trace error is in sub-meter level. On account of the external disturbance including wind action, water flow and soil bulge, the comparison error has a tendency to increase over time. This challenge needs to be considered in the future research.

4 Path Planning

The development of mobile robots are increasing rapidly in a lot of automated environments such as service robots for restaurant, transferring robots for moving goods in a factory, rescue robots for searching lives in the earthquake. In all these application, the mobile robots need to determine an adaptive paths according to the surrounding environments.

Before airboat autonomous navigation, the path planning is necessary for covering the whole paddy area. Two path planning methods were presented in this research. The first algorithm fitted to the rectangular paddy field. The input parameters include the beginning and end positions of the first path, the path number, turning direction and path spacing. Because this unmanned airboat platform is susceptible when the nature wind is stronger than 7 m/s. The second algorithm utilized wind direction in a while to make a path map which is parallel to the average wind direction. The proposed algorithm is suitable to match any shapes of the convex quadrangular paddy fields or ponds. In fact, some paddy fields are not convex quadrangle, are concave polygons,
even the edges of the paddy field are curving. So, this algorithm needs to be improved much more intelligent to adapt the different shapes of paddy farmland.

At the current stage, this two path planning algorithms can be just used in a rectangle and a convex quadrangle area, respectively. However, some unconsidered paddy fields or ponds are the shapes of irregular polygon. The edges are even cambered. In the future, this algorithm needs to be developed into much more intelligent to adapt the different shapes of farmland. In addition, the safety issues and obstacle avoidance should also be taken in account.

5 Autonomous Navigation

Autonomous navigation is the core research in this dissertation. All descriptions including the attitude estimation, mathematical modeling and path planning served for autonomous navigation. In the research, three potential solutions were proposed to make the unmanned airboat run on the predefined path map and avoid the external influence like the person and the edge of paddy field.

The first solution used a GPS compass, which can provide the global position and heading of the airboat, to compare the navigation error between the position of airboat and the path map by using LOS guidance law. Combine the environment of paddy field and the features of farming works in paddy field, a differential GPS compass (V100, Hemisphere GPS) was selected in this research to fix on the top of the engine safety shield. The original orientation of the GPS compass was set as the same direction with the heading of the airboat. This GPS compass can provide not only the position, but also the heading angle information. A recommended standard 232 (RS232) port was used to communicate with the computer on the airboat. Besides the DGPS receivers in
the robust packaging enclosure, a gyroscope was attached to the circuit board. When the GPS heading is lost due to the obstruction of satellites signals outdoors, the GPS compass also can execute the cruise navigation. The path map based navigation is the combination of the straight path following control and turning control. The farm works can be conducted based on whole path map based navigation. The experiment result showed that the RMS of lateral error was less than 0.24 m on the straight line.

The second solution was to develop an air station which consisted of a hexa-copter-UAV, a wide-angle camera, a Bluetooth transmitter and battery system to recognize the location of the airboat refer to the paddy field. The hexa-copter UAV (Zion AC940, enRoute) was used to be the platform of the air station. The standard payload of this UAV is 6 kg. The all airborne devices could be easily fixed on the aerial gimbal system of the UAV. The controller of the UAV is based on a Pixhawk autopilot board (3D Robotics) which is a high performance autopilot-on-module suitable for the UAV. The matched open-source firmware can make the UAV keep self-balance and height keeping flight. In order to recognize the paddy field and the airboat location, a mini computer (GB-XM1-3537, GIGABYTE), a digital camera (DFK 23UX174, Imaging Source) and a Bluetooth transmitter (Parani SD1000U, SENA) were attached on the UAV. The accuracy of the navigation is the RMS of lateral error was not over 0.17 m. This type of the airboat is suitable for spraying the liquid herbicides through the spraying hole at the bottom of the airboat. Because of the particle diffusion effect, the liquid herbicide can dissolve and diffuse into the water in the paddy field rapidly. It means that this navigation accuracy is enough for this spraying pattern in the paddy field.
The final one was a low cost solution which used a laser scanner to calculate the position relation between the airboat and the edge of the paddy field by using Otsu thresholding method. A servo-drive two DOF PTU was mounted on the top of the holder. A 2D laser scanner (UTM-30LX, Hokuyo) was fixed on the PTU, as a navigation sensor. The maximum detection distance is 30 m. The scanning range is forward 270° with a 0.25° angular resolution. The scanning frequency is 40 Hz. In addition, the IMU (VN100, VectorNav) was attached in the same coordinate system with the laser scanner to provide the attitude estimation. The computer on airboat was used to connect to the laser scanner and IMU for data processing. Although this laser scanner can provide wide detection range, the ahead 180° of detection range was used in the research. This solution applied to the small paddy field with straight edge. The experiment result indicated that the RMS of lateral error was about 0.18 m. In addition, no matter for the farmers in paddy field, or for the airboat itself, navigation safety is required to consider invariably. The attached laser scanner on the front of the airboat is not only a navigation sensor, but also a safety sensor which can measure the distance from the obstacle to the airboat. Define a safety threshold, if the measured distances from obstacles are less than the threshold, the airboat can stop and wait until the obstacles are removed, or steer back to avoid the obstacle. If a person was detected in the appointed unsafe region, the airboat would stop and wait until the person moved out. If an edge of paddy field was detected, the airboat would turn to next target path. Every field experiment showed that the navigation accuracies were satisfactory to the requirements of weeding and fertilizing in paddy field.

In this study, three solutions were proposed on autonomous navigation for the agricultural unmanned airboat in paddy field. Every solution devoted to make the
unmanned airboat follow the predefined path map, as well as avoid the external influence such as the nature wind, tall buildings and high cost.

6 Conclusion

In order to realize automatically weeding and fertilizing by an airboat in paddy field, autonomous navigation is the core research in this dissertation. All mentioned descriptions including the attitude estimation, mathematical modeling and path planning served for autonomous navigation. Three navigation system based on a GPS compass, an air station and a laser scanner respectively, were proposed to make the unmanned airboat run on the predefined path map and avoid the external influence like the person and the edge of paddy field. The result of the performance in each navigation system showed the navigation accuracies were acceptable to meet the requirement of weeding and fertilizing in paddy field.