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Development of Unmanned Surface Vehicle for water quality monitoring and measurement

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Abstract

Water qualities management for the water reservoir are becoming unprecedentedly more important due rapid growth of populations and high tech industries, furthermore, recent climate change also play an important role into this problem. Regular water inspection and sample collection could help significantly in management of water resources also the distribution of water. Even though the testing of water is mostly done by the senor station in water reservoir automatically, but only small number of the station are installed in the reservoir, hence the "resolution" is not enough for modern day uses. Apart from the resolution, the state of the art water management uses the results of water measurement (sample collected by inspector) for further decision making. Such method is accurate but lack of real time information which leads to slow in the response when pollution or after natural disaster. In order to solve these problem, many researcher has start to uses Internet of Thing (IoT) concept sensors, however, the cost is still high, as well as that many water reservoir did not have mobile phone signal coverage. Hence, this paper propose and development of Unmanned Surface Vehicle (USV) which carry a mobile water quality sensor to perform a real time scan of water qualities. Secondly, due to no mobile signal coverage, development will also include the communication relay via UAV.

Key words: Water inspection, Unmanned system, Unmanned surface vehicle

Introduction

The water quality in the current water supply system become very important. According to the Environmental Protection Administration Executive Yuan in Taiwan, there are 3.2 billion cubic meter of waste water in Taiwan, and around 1.1 billion cubic meter are industrial waste water (around 34%), therefore continuous water monitoring is essential. Taking Taiwan as example, there are 53 water reservoirs with total 1.8 billion cubic meter and cover area 4930 kilo square meters, and state of the art inspection method only inspect two to three point of each water reservoir which no longer fit the current situations. Using Feitsui Dam [3] as example, the water inspection cost raise from 3 million NT dollar in 2013 to 22 million NT dollar in 2017 because of the increased area of inspection and more detail analysis of the chemical compound in the water. However, according survey by Crooks [4], more than 60% of the cost are labor cost and sample cost, the actual analysis cost is very low, hence, if one want to increase the inspection frequency for water reservoir but still maintain the cost, then automation is a must.

Selection of Water sensors

Instead of collecting sample for inspection, this project also selected a continuous monitoring sensor. ARK sensor System from AQUAS [4] is selected, and measurements are as follow: 1) Chlorophyll-a , Chl-a, 2) Dissolved oxygen, 3) Electrical conductivity , 4) Potassium ion, 5) pH, 6) temperature and 7) Turbidity. Even though ARK system can give multiple reading at same time, but the hardware itself was designed for stationary point monitoring, therefore to have a water reservoir to equip "Enough" ARK system will be not be economically possible, hence, the this project will make the ARK system become "MOBILE"

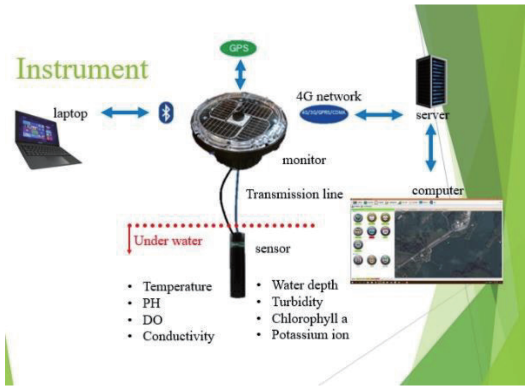

Fig 1. ARK sensor system and GUI for display measurement data.

Design of USV- case study

Before the design of the actual USV, the first case study is required to understand the actual inspection operation, the research team has bring the GPS recording system on board of the patrol boat (belong to water reservoir) and visit all the "current" inspection point"
The full operation require almost 2hr, with inspection of 5 points by using ARK system and total of 20L of water sample are collected. Each of the inspection require the ARK system to stay around 2 to 5 min depends on the wind and wave speed. In this case few conclusion are drawn:

- The sampling location – one point in the area, not accurate enough. Area scan could incase the accuracy but the scan speed must match the sensor reading time.
- Apart from the sensor measurement, water sample collection is required, and because for different type of chemical analysis, therefore require certain amount of sample (more than 1L)
- Weather has significant effect for the inspection

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mission, but also contamination spare fast in bad weather (such as heavy rain and strong wind)

- Each inspection mission will require at least 3 people (one for driving the boat, two for water sample collection and monitoring).
- Boat's propeller has high chance get jam on the grass when close to the shore.
- Boat fuel is enough to run point to point in the water reservoir, but not enough for scanning of the whole area.

Fig 2. Top left, the patrol boat. Top right, collecting sample. Bottom: Path of the patrol boat.

Above points are the problems or function that USV must have.

Design of USV- decision of the platform

The conventional boat is a single hull design, which has low friction and good stabilities in water. This type of design has been around for the thousands of years, therefore it is been proved its usefulness. However, during the bad weather, the single hull (in this case) has difficulty to operate, and USV will require to overcome such problem, therefore, analysis of the intact stabilities is required.

First, assuming the operation is in the bad weather where the water wave could be as high as 1 meter height with cycling time of 5 second, then according wave energy equation in (1) [5]

C = Wave speed

T = cycle in second = 5

$C = 1.56T$ (1)

Assume water volume weight (γ)=10.3 KNm^{-3} , so energy of wave can be written as:

W_{wave}=1/16 γH^2C=0.0975γH^2T=1004.25H^2T (2), therefore, plug in cycle time and wave height, the total wave energy will be:

W_{wave}=6468.4997

Now, in this stage of the project, the USV must be in the size that able to fit into normal car for easy transportation, therefore the research team uses small toy model boat that has length of 0.68m and height of 0.28m. With standard ship stabilities analysis (due to the analysis is complex, which is outside the scope of this paper, therefore only the results will be shown in this paper, however, the detail of the equation and calculation can be found in [6]). Analysis consider both single hull and double hull design.

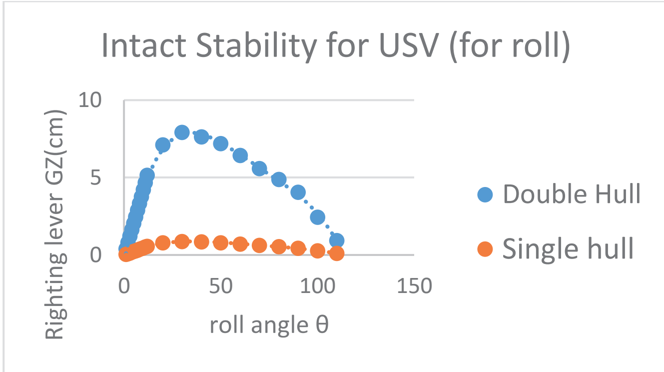

Fig 3. Intact Stability for USV with single and double hull design.

With the GZ curve, it is very clear that double hull has better stability compare with single hull, however, energy analysis is still needed, therefore by using (3), (4) and (5) from [6]

$dW = M \times d\theta$ (3)

$M = F \times \overline{GZ} = \tau$ (4)

Hence, the energy that a hull can take is:

$W_{boat} = \int_{\theta_1}^{\theta_2} \tau \, d\theta$ (5), and if plug in the double hull design, then the total energy is :

$$W_{boat} = \int_{\theta_1}^{\theta_2} \tau \, d\theta = \int_{0}^{110} F \times \overline{GZ} \, d\theta = 6510.6763 \text{ (J)}$$

Which compare with wave energy that calculated before: $W_{boat\ DH} > W_{wave} > W_{boat\ SH}$. Hence, the double hull design is safer to be use (allow to operate in the bad weather).

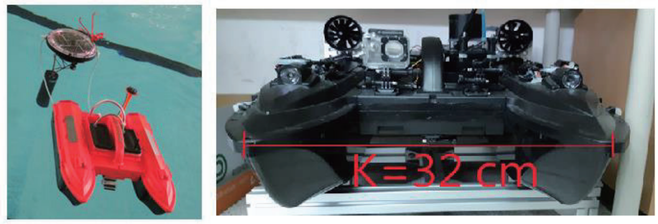

Fig 4. Left, double hull USV. Right, USV with ducted fan

Design of USV- Extra thrust system

The USV is a double hull design boat with using external under water thruster for its primary power system. Even though the underwater thruster has better efficiency but can be jammed when FOD which is very common when operate near the side of the mountain or shore of the water reservoir. In this project, the team from CYCU has installed a second power unit which base on "ducted fan"(Fig 4, right). The second system can only provide emergency usage because it efficiency is low and can be easily effected by weather (strong wind will cause the system to lower down output force)

Modeling of the surface vehicle

In this project, the dual hull boat is selected, therefore motion/control model must be developed for programming the

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autopilot. The main propose of the vehicle is to carry water quality sensor and capture sample, therefore active platform stabilization is not a concern, hence, the design can be simplified. Without the active stabilization fin for roll compensation and water resistance, a double haul boat (with rudder for each haul) motion model can be consider to be similar to vehicles with differential-drive steering (Fig 3).

Let represent the instantaneous radius of curvature of the robot trajectory, and W to be width between tow motors, therefore following equation can be builds base on the velocity of each haul: ($\psi^{\cdot}$ is the rate of the heading angle)

$v_{left} = \dot{\psi}(\mathrm{R} - \mathrm{W}/2)$ (6) and $v_{right} = \dot{\psi}(\mathrm{R} + \mathrm{W}/2)$ (7)

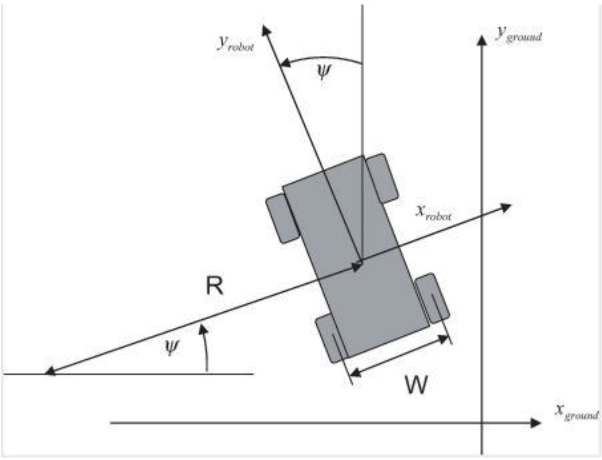

Fig 5. Differential drive steering robot

Speed different between right and left haul is:

$v_{right} - v_{left} = \dot{\psi}\mathrm{W}$ (8)

Hence, the vehicle heading angle rate can be written as:

$\dot{\psi} = \frac{v_{right} - v_{left}}{W}$ (9)

Or intern of turn radius R:

$\dot{\mathrm{R}} = \frac{v_{left}}{\frac{v_{right} - v_{left}}{W}} + \frac{W}{2}$ (10)

therefore, R will be:

$R = \frac{W}{2}\frac{v_{right} + v_{left}}{v_{right} - v_{left}}$ (11)

Next, the expression of velocity along the vehicle's longitudinal axis is:

$$v_y = \dot{\psi}R = \frac{v_{right} - v_{left}}{W}\frac{W}{2}\frac{v_{right} + v_{left}}{v_{right} - v_{left}} = \frac{v_{right} + v_{left}}{2}$$

However, if putting all the velocity components along the vehicles coordinates:

$v_x = 0$

$v_y = \frac{v_{right} + v_{left}}{2}$

$\dot{\psi} = \frac{v_{right} - v_{left}}{W}$

If convert above velocities though Euler angle to earth coordinate, then the velocity in X and Y coordinate will be as follow (Z coordinate is not in the consideration due to the vehicle assume only operate on surface without changing depth or altitude):

$\dot{x} = -\frac{v_{right} + v_{left}}{2}\sin\psi$ (12)

$\dot{y} = \frac{v_{right} + v_{left}}{2}\cos\psi$ (13)

Equation (6) ~ (13) are all the physical modeling of the motion of the vehicle, which can be program into vehicle autopilot system with navigation data from GPS coordinate. To further reduce the complexity, the forward power for the vehicle is fixed (differential only happen in turning).

Autopilot firmware and software

Autopilot system and software is based on the autopilot system that the research team in CYCU has previous developed. However, few modification are made to adapt the control of USV and also the mission display match to real ship operation.

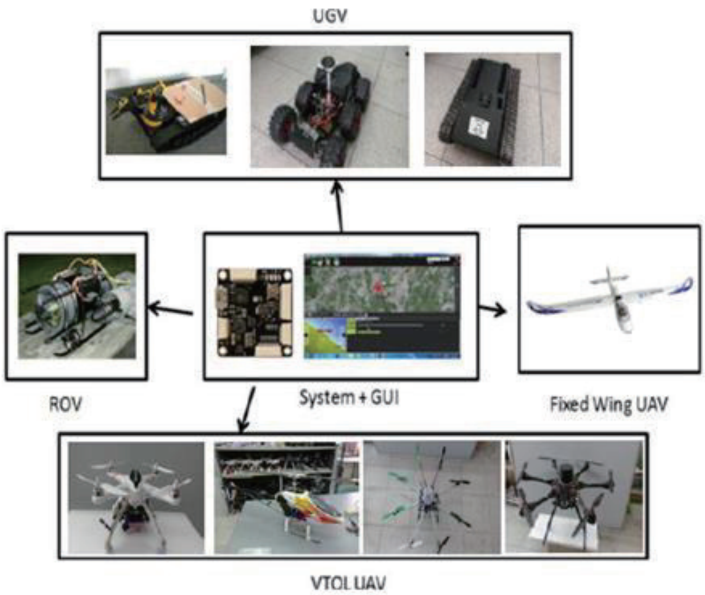

Fig 6. Autopilot and software system from CYCU team [7]

Field Test & Results

The water reservoir for inspection in this case is the BaoShan water reservoir, and tests were carried out in two different weather condition and also different inspection path to ensure the reliabilities of the system.

First experiments were carried out in the windless day during summer in 2017, due to the size f the chosen boat, it was not able to finished scanning the whole area of the water reservoir, and however, the overall mission was carried out fully automatically, which shows the usefulness of the system.

Second experiments were carried out in the same area but with wind speed up to 12m/s at ground (scale of 5 to 6 wind) with lightly shower. The unmanned boat was still runs autonomously with GPS, however, this experiments shows

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such condition is operable, but not recommended due to energy consumption become very large due to strong wind and waves.

Third experiment carried out in early 2018 with different inspection path. Inspection mission is fully success with all the inspection equipment, however, at this stage, the sample collection is still on development.

Secondly, wireless communication were only up to 1 km in all experiment due to problem of line of sight, however, for real scanning mission, the travel distance will be larger than 1km and condition will also not allow line of sight, hence, this project also require non-line-of-sight communication system, which were also developed by the CYCU team in other project [7]

Fig 7. Left, USV with sensor. Right ground control station for USV operation

Fig 8. Left, the planned mission. Right, actual path of the unmanned boat –note, it match with the planned route very well.

Fig 9. Left, camera view with good weather, right, with 11m/s wind and shower.

Fig 10. Second inspection path. Note blue is the actual path, yellow points are the pre-set way point.

Fig 11. Testing of the communication relay system, user signal is send from laptop to UGV via UAV [7]

Conclusion

This project has successfully created the control system for the double hull USV, and has been proved in the field with two different type of weather conditions and different inspection route. However due to physical size of the vehicle itself, the full scan of the water reservoir was not possible, therefore, this will be the first point for the future improvement.

Secondly, the "ducted fan" system for USV proved its usefulness, but it can be only used for backup system.

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