Proceedings of 2019 IEEE
International Conference on Mechatronics and Automation
August 4 - 7, Tianjin, China

Improvement and Evaluation for the Stability of Mobile Spherical Underwater Robots (SUR III)

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***Abstract* - This research aims to improve the collaboration ability and stability of the Spherical Underwater Robots (SUR III). According to our previous researches in last few years, the SURIII has no control stability module. This paper designed a new torque gyro control and PID control devoted to improve the stability of SUR III. In this new system, we used a gyro sensor and PID control to design a closed-loop control module to perform terrestrial underwater efficiently. Regarding the spherical robot mechanical structure and dynamic model, the robot control module is designed, and set up to complete underwater experiments. In the underwater experiment, the SUR III can stability motion. A certain offset occurs of SUR III under the disturbance of the wind. After the adjustment of the balance control module, the SUR III balance is quickly restored. In addition, it is certainly worth analyzing the underwater motion to evaluate the performance of the robot stability motion.**

Index Terms - Proportional–Integral–Derivative Control, Underwater Balance Control, Spherical Underwater Robot

I. INTRODUCTION

Underwater vehicles have achieved significant developments over several decades ever since the 1980s.AUVs or Autonomous Underwater Vehicles are robots, which are designed to navigate underwater environments without any human intervention [1]. AUVs play an important role in oceanographic study, such as submarine reconnaissance, construction of offshore gas and oil facilities [2]-[5]. Since underwater robots have different applications, the underwater robots have different structures, sizes and propulsion modes. In order to easily enter some small places, design underwater robots flexible and low-speed [6]. Motion control, such as heading control, depth control and trim control, is a key technology urgently needed to be studied and solved in many key technologies of AUVs. It is an important technical guarantee for the completion of AUV mission.AUV is a typical system with nonlinear, coupling and hydrodynamic uncertainty of motion model. The complexity of the model and the disturbance of the current will make the precise motion control very difficult. To satisfy the demanding control requirements, many control architectures have been developed. Such as, the hierarchical architecture, the sub-Sumption architecture, and the hybrid architecture [7].

The stable motion control of the underwater robot is one of the main parts of majority underwater robot technologies. Research on designing of AUVs motion control algorithm has attracted researchers' attention and many researchers around the world deal with challenges due to the uncertainty of AUV dynamics expressed in ocean currents and waves of shallow water in shallow water, as well as other issues related to the intended mission [8]. When the AUV rises to the surface and receives positioning signals such as GPS to ensure its course will be affected by waves. Many researchers around the world face challenges due to the uncertainty of AUV dynamics and other issues are related to the expected tasks. However, due to the dependence of AUV dynamics on the external environment, the autonomous navigation and control of AUV in the Marine environment are limited. There are empirical methods reported in literature for controlling the algorithms of AUV such as proportional-integral-derivative controller, self-adaptive control, fuzzy PID control [9], sliding mode control, neural network (NN) control, robust control [10] and the combination of several control methods, etc. Raja Rout et al. proposed an PID control method with inverse optimal self-tuning which used a NARMAX model and an adaptive tuning system to develop a control strategy that can control depth and heading motion of the AUV [11]. Incorporating adaptive control with anti-windup compensators to provide a convenient combination to counteract the challenge is embedded with a PID controller was raised by researchers in Babol Noshirvani University of Technology [12]. Xianbo Xiang et al. present proposed a two-layered framework synthesizing the 3D guidance law and heuristic fuzzy control can achieve robust adaptive following along a predefined path [13]. In our previous researches about spherical underwater robots, we designed a spherical robot that improved propulsion system to increase the stability [14]. Our team's also design a novel mechanical method of stability system to improvement for underwater robot [15].

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And then, we design a novel propulsion system to improve stability for the spherical underwater robot [16]-[18].In the follow up study, an amphibious spherical robots' system was proposed, it realized the robot move on land and underwater[19]-[21].In this paper, AUV dynamics is identified using a gyroscope module and an adaptive tuning for the PID controller. This paper presented a controller of the AUV that can improve the stability for the form of ocean currents and waves on the surface on the water. The rest of the paper is organized as follows. Section II introduces the structure of SUR III, including the overall structure and control structure. The dynamic equations of the spherical underwater robot. Also, with some basic assumptions about the PID control method are introduced in Section III, and experiments and experimental results are provided in Section IV. Finally, conclusion is provided in Section V.

II. System Related Works

A. Spherical Underwater Robots

Spherical underwater robots were developed with high mobility and high flexibility in previous researches [22]-[25]. The robot consists of a spherical body and four propulsions. Fig. 1 shows the 3D model of the SURIII is illustrated. Sensors, control circuits, etc. are collected in the waterproof bin [27]-[31]. Motor, propeller and vectored water-jet thrusters form the power part of the dynamical system. Support frame are used to hold up the waterproof bin in the hull. Four vector water jet thrusters require four symmetrical openings to accommodate the spherical hull. The robot has a diameter of 490 mm and its net weight is about 7.9 kg.

B. Equation of Dynamics for Spherical Underwater Robots

In order to improve the stability of spherical underwater robots, controller should generate suitable control law.

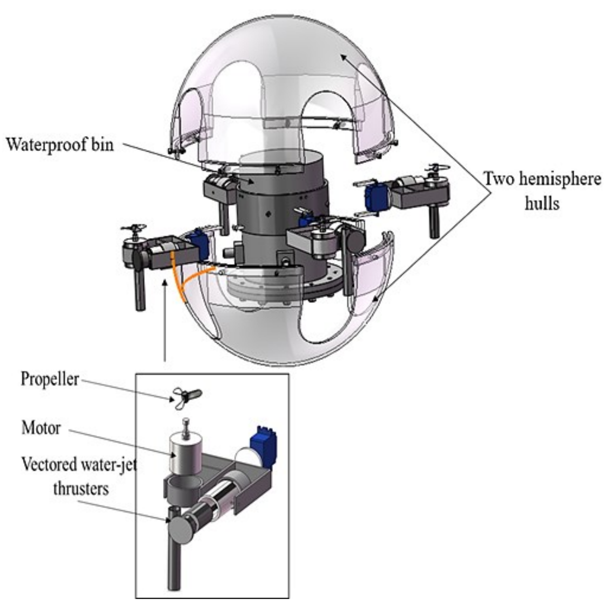


Fig 1. 3D model of SURIII.

Firstly, we obtained the dynamic equation of underwater robot [26], [32]-[34].

The expression for dynamics equation of an AUV is given as,

$$M_B \dot{v} + C_B(v)v = \tau_B \tag{1}$$

where $M_B \in R^{6\times6}$ is the sum of system mass matrix and added mass matrix,$\dot{v}$ is the vector of generalized accelerations, $C_B \in R^6$ is the Coriolis and centripetal matrix., $\tau_B \in R^6$ is the vector of generalized forces which input by control system. AUV is affected by the force include the propulsive force and moment, wind and wave that vectors of forces generated by wind and wave on the surface of the water. The equation of AUV force in the fluid as,

$$\tau = -M_E v - C_E(v)v + F + F_w \tag{2}$$

where M_E is the mass matrix of the fluid that the additional mass corresponding to the AUV, F is the force include the propulsive force and moment, buoyancy and fluid mechanics, where F is related to the damping matrix and the vector of restoring forces and moments. F_w is applied external force such as wave force. In order to simplify the controller design, few assumptions are made throughout the paper i.e.

Assumption 1: All the states of dynamic equations are able to be measured.

Remark 1: Considering the physical constraint or cost of the sensor system, Assumption 1 is not true all the time. However, an observer can be designed to estimate the unmeasured states of the AUV [35]-[37].

Assumption 2: The effect of edges of the hull and the support of propulsion system on motion is zero.

Remark 2: For our spherical underwater robots, the inclusion of these terms complicates the structure design with no significant in the stability performance [38]-[40]. Unlike a fully actuated vehicle, the effect of structure is significant, so our spherical underwater robots can be neglected for the structure design.

Assumption 3: Pitch angle and pitch rate are assumed to be zero.

Remark3: The underwater robot including surge, sway, heave, roll, pitch and yaw in six degrees of freedom. According to the summary of the utilization of different

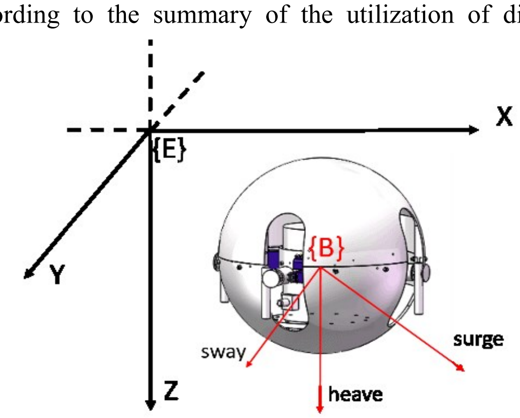


Fig 2. Definition of AUV frames.

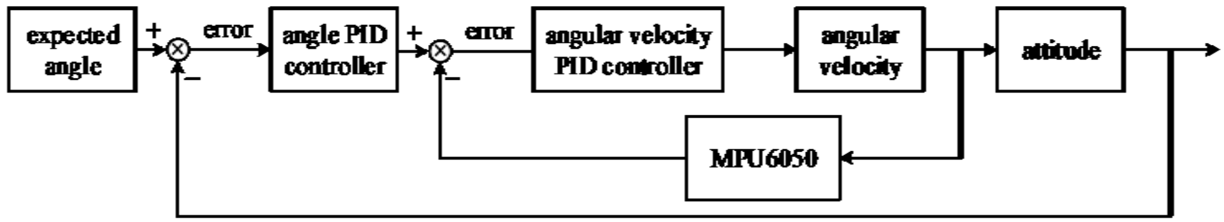


Fig.3.PID control overall flow chart.

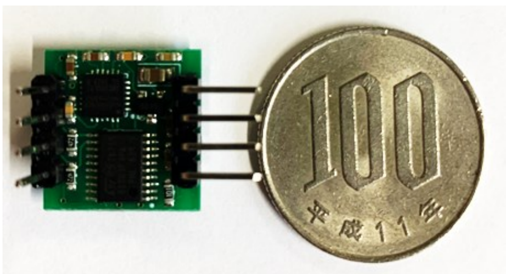


Fig. 4. MPU6050 stability sensor.

degrees of freedom of underwater robots, swings, scrolling and pitching are rarely used in reality.

When modelling the movement of a six degree-of-freedom underwater robot, by two reference coordinate systems. Referring to Fig. 2, surge, sway and heave axes denote the linear positions along whereas pitch, roll and yaw are the angular positions along axes of the AUV.

The attitude is used to describe the angular positional relationship between a fixed-frame coordinate system and a reference coordinate system of a rigid body. The attitude matrix and the data required for the calculation of the carrier's attitude and navigation parameters can be obtained, which is an important task in the strapdown inertial navigation algorithm. The attitude and heading of the carrier embody the azimuth relationship between the carrier coordinate system and the navigation coordinate system. Determining the azimuth relationship between the two coordinate systems requires the displacement theorem of the rigid body fixed point motion in the matrix method and mechanics.

At present, there are various methods for describing the azimuth relationship of the moving coordinate relative to the reference coordinate system, which are generally classified into three categories, namely, a three-parameter method, a four-parameter method, and a nine-parameter method.

The three-parameter method is also called the Euler angle method, the four-parameter method usually refers to the quaternion method, and the nine-parameter method is called the direction cosine method. The Euler angle method cannot be used on a full-pose carrier, so it cannot be widely used in engineering practice. The direction cosine method has a large amount of calculation and low work efficiency. There are three-axis flips of AUV as it should worked underwater, and the quaternion method can be more conducive used on the AUV. A quaternion can describe the rotation of a coordinate system or a vector relative to a coordinate system. The scalar part of the quaternion represents the half cosine of the corner, and the vector part represents the direction of the instantaneous axis, the cosine of the direction between the instantaneous axis of rotation and the axis of the reference coordinate system. The solution of the attitude angle is divided into two steps. Firstly, attitude matrix the following equation (3):

$$C_E^b=\begin{bmatrix}\lambda^2+P_1^2-P_2^2-P_3^2 & 2(P_1P_2+\lambda P_3) & 2(P_1P_3-\lambda P_2)\\ 2P_1P_2-\lambda P_3 & \lambda^2+P_2^2-P_1^2-P_3^2 & 2(P_2P_3+\lambda P_1)\\ 2(P_1P_3+\lambda P_2) & 2(P_2P_3-\lambda P_1) & \lambda^2+P_3^2-P_1^2-P_2^2\end{bmatrix} \tag{3}$$

Secondly, carrier attitude angles the following equation (4):

$$\begin{cases}\theta=-arcsin\left(T_{13}(n)\right)\\ \theta=arctan\left(\frac{T_{12}(n)}{T_{11}(n)}\right)\\ \theta=arctan\left(\frac{T_{23}(n)}{T_{33}(n)}\right)\end{cases} \tag{4}$$

C. Basic Assumptions about the Environment

Ocean wave is a periodic movement under the action of gravity after the disturbance of sea surface pressure. Waves usually refer to wind waves and surging waves. The wave force of underwater objects is mainly generated by surging waves. For spherical underwater robots, we mainly consider the influence of surging waves. In this paper. The simulated robot is affected by waves on the sea surface that we impose human interference on a moving robot.

III. Stability Unit and PID Simulation Results

PID controller has been widely used in various fields that has many advantages, such as simple structure and good stability. PID control overall flow chart in Fig. 3. It is the integral quantity and the micro component, k_i, k_d. For proportional, integral, and differential coefficients. The integral amount and the differential component are discretized to obtain the PID calculation formula. The PID calculation formula the following equation as,

$$\mathrm{U(t)}=k_pe(t)+k_i\sum_{j=0}^{t}e(j)T+k_d\frac{e(t)-e(t-1)}{T} \tag{5}$$

Where T is the update time. The input quantity of PID control is based on the error between the feedback quantity and the desired value, the input quantity is calculated by proportional, integral, differential, and the sum of them is to obtain control axis Euler Angle. The gyroscope samples the triaxial angular velocity and the acceleration sensor samples the triaxial

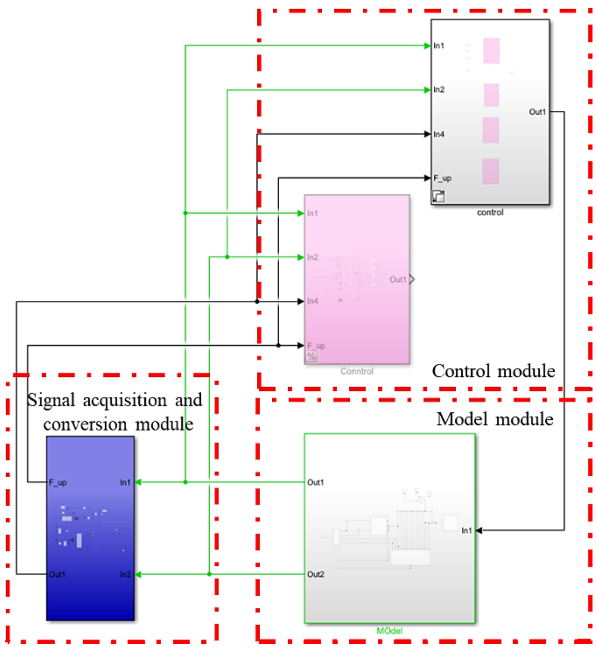


Fig. 5. Overall structure of simulation model

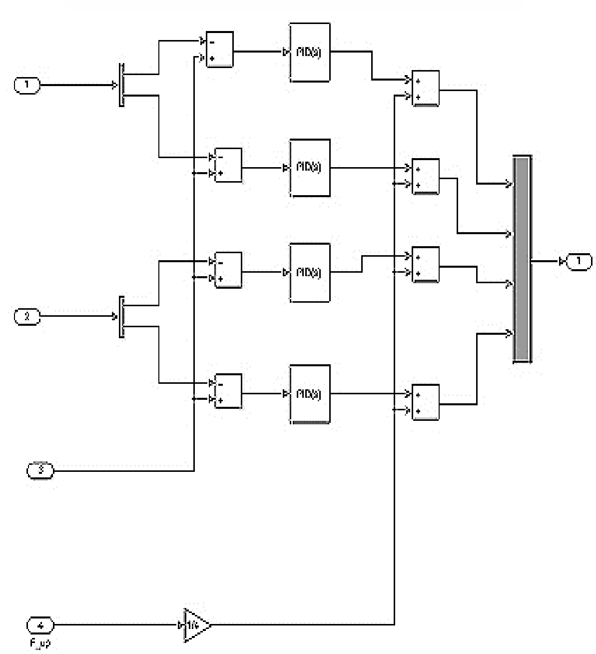
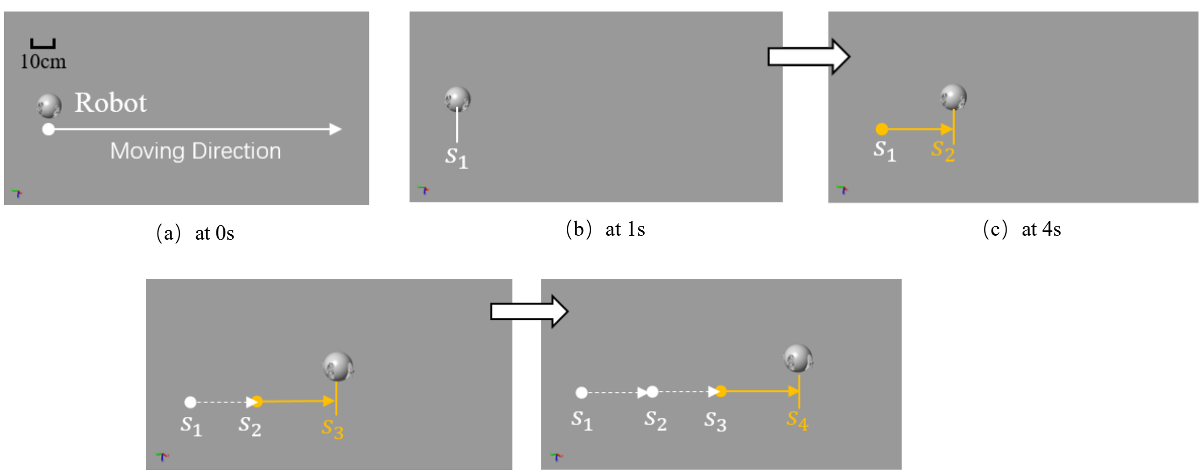


Fig. 6. Control model of Simulink



(a) at 0s

(b) at 1s

(c) at 4s

(d) at 7s

(e) at 10s

Fig.7. Motion simulation results

acceleration. The triaxial Euler Angle is obtained by calibrating, filtering and correcting the sampled data of the quantity. The attitude solution is used to calculate the three - gyroscope and acceleration sensor. Gyro accelerator MPU6050 is shown in Fig.4. It has a high-precision connected to the main control processor through the I2C bus. The x-axis, y-axis, and z-axis angles are measured by integrating the internal pose calculator and the dynamic Kalman filter algorithm. We calibrated the gyroscope due to the device error of MPU6050. In the initial state, the angular velocity should be 0°in the gyroscope is stationary. We sampled the data 500 times in the gyroscope is stationary, and then averaged it to obtain the offset and calibrate the gyroscope data. When the underwater spherical robot advances normally, the interference of the sudden wave may cause the Euler angle error calculated by the attitude, and the system is difficult to operate stably with the angle single ring, so the angular velocity can be added as the inner ring. The angular velocity is output by the gyroscope. The collected value generally has no external influence, strong anti-interference ability, and the angular velocity changes sensitively. When it is interfered by the outside, the response is rapid. The angle is used as the outer ring, and the angular velocity is used as the inner ring to perform attitude PID control. Among them, the PID output is the PWM value, the PWM value is given the electronic governor value, and the electronic governor controls the motor to change the spatial three-axis Euler angle. According to the formula, the control algorithm of the attitude PID can be obtained. Angle ring PID the following equation as,

$AngelPID\ Out(t) =$

$$k_p e(t) + k_i \sum_{j=0}^{t} e(j)T + k_d \frac{e(t)-e(t-1)}{T} \tag{6}$$

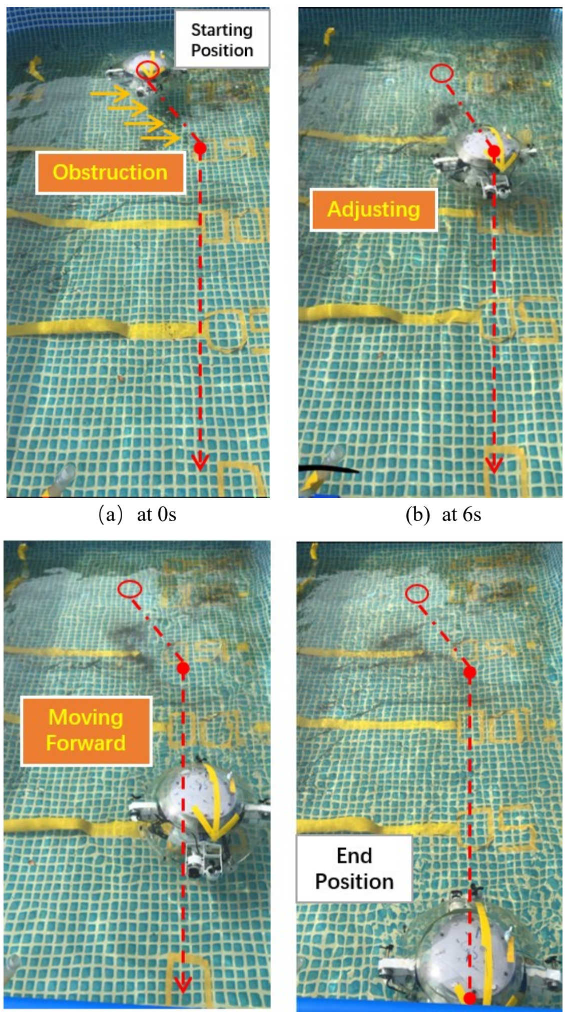
Angular acceleration ring PID the following equation as,

$AngelRatePID\ Out(t) =$

$$k_p' e'(t) + k_i' \sum_{j=0}^{i} e'(j)T + \ k_d' \frac{e'(t)-e'(t-1)}{T} \tag{7}$$

IV. Experiment and Results

To demonstrate that the PID control is suitable to our underwater spherical robot, some simulation experiments are conducted. Simulink simulation environment in MATLAB has powerful modularization and graphical modeling and simulation ability, which is an important tool for the simulation of underwater vehicle motion and control system.



(a) at 0s (b) at 6s

(c) at 12s (d) at 18s

Fig. 9. Straight forward motion

According to the mathematical model of underwater vehicle motion, the simulation model is built in Simulink environment that as shown in fig.5.The control model of Simulink as shown in fig.6.

Set the initial velocity of the SUR III is 10 cm/s, and advance 10s from the sea level. The simulation results as shown in fig.7. 0s to 1s is the process of anti-interference and SUR III recovered balance. After 1s, the SUR III moves forward and maintains its balance within 10 seconds. During the forward motion that two disturbances are added at 4s and 7s respectively, and the balance can be restored by control system. The simulation results as shown in fig.8. The ordinate in fig.8 represents the distance between the centre point of SUR III and the water surface, and abscissa is the time. SUR III is removing in the balance position and the it can recover its balance after applying disturbance at 4s and 7s that can maintain its equilibrium state.

For evaluating the performance of the balance control system, experiment is conducted in this section. A swimming pool is prepared with the water at the depth of 60cm.It is 3 meter in length, 2 meter in width. The experimental setup is shown in fig.9 (a). The forward-moving video sequence took approximately 18 second. Due to the influence of the wind, an offset occurred at the advance of 6 seconds (Southeast wind,6m/s). Through the PID control adjustment, the SUR III restores balance after the offset. The experiment process is shown in fig.9 (b-d).

V. Conclusions

This paper presented a control system for the third-generation spherical underwater robot (SUR III) that improve the stability in the sea surface. First of all, the general underwater is proposed to explain the basic theory of the stability control. Due to the better performances as strong robustness, and the algorithm is simple, easy to understand and master, PID control are employed as the stability control modules for the SUR III. Then, this design contains a stable, trapped, closed loop control module. Through the advanced gyro sensor MPU6050, three parameters of acceleration, angular velocity and rotation angle along the x-, y- and z-axes are measured. Finally, we use the Simulink of MATLAB software to simulate AUV advance on the sea surface. AUV is removing in the balance position and the it can recover its balance after applying disturbance at 4s and 7s that can maintain its equilibrium state. Due to cross-flow, the robot has a certain deviation, which will further improve the problem. For evaluating the performance of the balance control system, experiment is conducted. The forward-moving video took approximately 18 s. Through the PID control adjustment, the SUR III restores balance after the offset that the influence of the wind.

Acknowledgment

This research is partly supported by National High Tech. Research and Development Program of China (No.2015AA043202), and SPS KAKENHI Grant Number 15K2120.

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