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A self-balance system for naval operation vehicles

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Abstract. For the purpose of maintaining the balance of the deck of naval vehicles while they are maneuvering on the water surface, a simple mechanism with a feedback control scheme is designed to detect and compensate the external disturbances. To avoid complex mathematical modeling for high degree-of-freedom mechanism, a simplified mechanism adopted from the novel Stewart and delta designs is developed. Incorporating with the inertial measurement unit (IMU), the proposed framework is able to drive the mechanism by servomotors to achieve the goal of balancing the vessel deck by detecting instant three-axis attitude data. Field experiments performed at a swimming pool demonstrated outstanding performance in deck balance by suppressing external disturbance from the wave.

Keywords: self-balanced, naval, operation, vehicle

1. Introduction

Marine vehicles including ships and boats are major transportation tools on the water. However, since those marine vehicles maneuver on the water surface, inevitable disturbances from the wind and the wave bring about imbalance of the marine vehicles. Although the gravity center of the marine vehicle is always designed to be lower than its buoyance center, the marine vehicle can maintain its stability for disturbances within design specifications. But shaking of the marine vehicle always causes uncomfortableness to people on the deck.

Nowadays, the three-axis stabilizer has been widely applied to cameras for image stabilization by using motors to compensate external disturbances [1]. The major component of the three-axis stabilizer is an inertial measurement unit (IMU) or a gyroscope device to acquire instant information of external disturbances [2, 3]. In addition, servomotors or actuators with controllers are also equipped to drive the mechanism to achieve the goal of eliminating disturbances [4]. There have been various mechanism designs for the stabilizer. The concept of those designs is either to improve the accuracy of the mechanism or make the mathematical modeling simpler [5]. Apparently, applications of the stabilizer are not limited to camera stabilization. Instead, oil drilling, radar systems and other operational platforms can perform much better if their platforms are built with the function of stabilization [6]. Therefore, this project extends the idea of stabilization to the naval operation vehicles. The objective is to develop a mechanical self-balance device attached to the deck of a marine vehicle with a feedback control scheme so that the device can preserve the level of the deck all the time by automatically counterbalancing unknown external disturbances. A scaled down model will also be constructed for the purposes of function and performance demonstration

2. Theoretical background and experimental components

2.1. System architecture

In order to suppress external disturbances from the wave and wind, an IMU SparkFun MPU-6050 was employed to acquire instant motion information caused by the disturbances as the feedback signal. Furthermore, a microcontroller Arduino Due board was used to read instant IMU data as inputs and compute the corresponding PWM signal output to control the servomotors, which are connected to the multi-dimensional mechanism. The flow chart of the system is shown in figure 1.
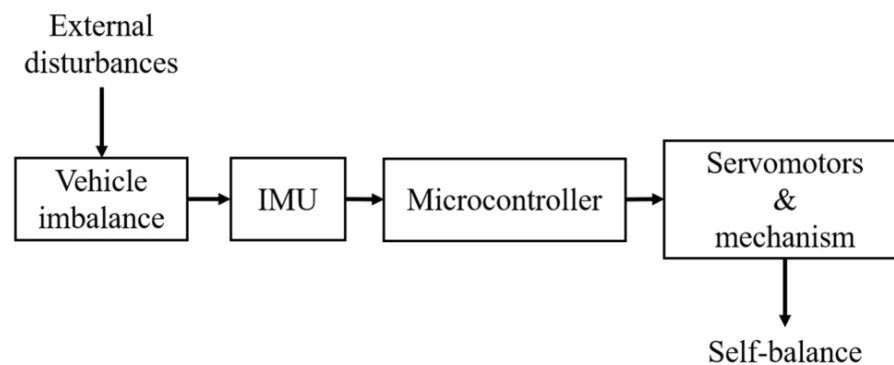

Figure 1. Flow chart of the self-balance system

2.2. The self-balance multi-dimensional mechanism

To avoid complexity of mathematical modeling for high degree-of-freedom mechanism, a simplified mechanism adopted from the Stewart and the delta designs was developed. Before the mechanism was actually built, computer simulations using SolidWorks as shown in figure 2 were conducted to assure the design is able to function properly without interference.

Components of the mechanism were manufactured by 3D printing technology, and the material PLA (Polylactic Acid) was chosen due to its versatility and robustness. Three servomotors assembled with toothed pully respectively to drive the mechanism by toothed belts and the deck is connected to the mechanism by ball joints in order to provide sufficient degrees of freedom for motion. The entire mechanism is shown in figure 3.
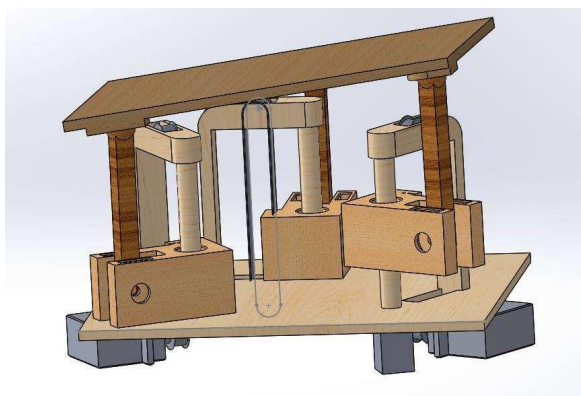

Figure 2. The mechanism designed on SolidWorks **Figure 3.** The actual self-balance mechanism

2.3. Linearization analysis of the mechanism

Geometric relationship needs to be solved to guarantee the rotation angle θ of the deck has a linear function with respect to the displacement d of the fork-like sliding block. Based on the geometric

relationship shown in figure 4, when the fork-like sliding block is moved with a displacement d, the rotation angle θ of the deck is given by $\theta_1 - \theta_2$,

$$l = \sqrt{(64 + d)^2 + 78^2} \tag{1}$$

$$\theta_1 = \cos^{-1}\left(\frac{78}{l}\right) \tag{2}$$

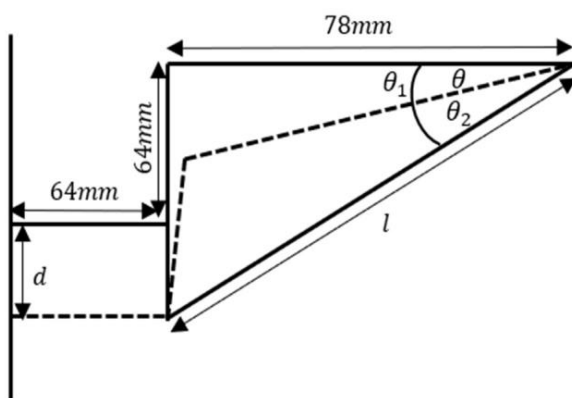$$\theta_2 = \cos^{-1}\left(\frac{l^2 + 78^2 - 64^2}{2 \times l \times 78}\right) \tag{3}$$

Figure 4. Geometric relationship of the mechanism

Table 1. Linear relationship between θ and d

Displacement d (mm)	Rotation angle of the deck θ (degree)
5	3.68
10	7.37
15	11.10
20	14.90
25	18.80
30	22.85
35	27.14
.	.
.	.

2.4. System steady state response analysis
Experiments were conducted to establish the transfer function of the system. Different PWM output signals were given by the microcontroller to drive the mechanism, and the IMU recorded the angular velocity of the deck every 10 ms. Table 2 shows the result at PWM = 1300, and the plot of the angular velocity versus time is depicted in figure 5.
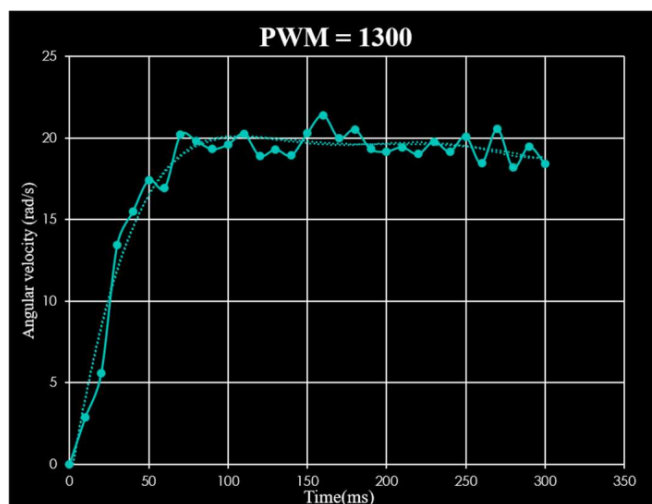

Figure 5. Time response of the system

Table 2. Experiment result at PWM = 1300

Time (ms)	Angular velocity of the deck (rad/s)
10	2.82
20	8.98
30	14.70
40	15.54
50	15.63
60	18.68
70	17.29
80	19.77
90	19.06

As a result, the system is reasonably approximated to be a first order system, and the time constant of the system can be estimated by the time when the system reaches 63.2% of its steady state value. After

the transfer function of the system is obtained, the block diagram of the system, illustrated in figure 6, can be established as a close-loop control system. Because the speed of the transient response of the system is desired to be fast, a PD controller for the controller G_c was selected and the parameters of the controller were tuned during field experiments to find the suitable ones.
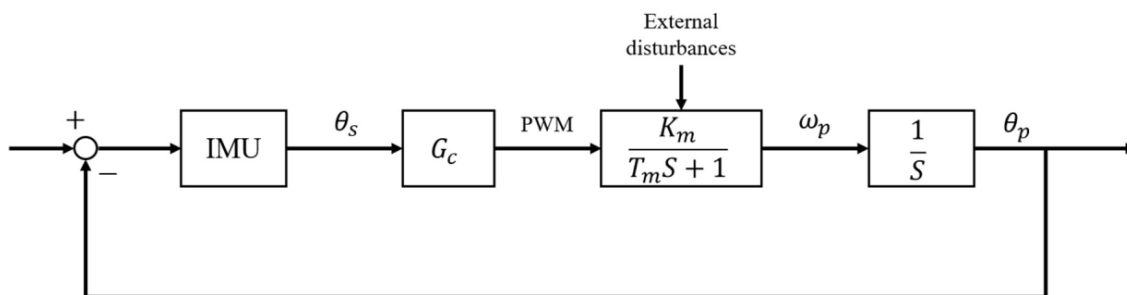

Figure 6. Closed-loop block diagram of the system

3. Results and Discussions

Field experiments were conducted at the swimming pool in the campus to demonstrate the function and performance of the proposed self-balance system, which is shown in figure 7. For better presentation for the results of field experiments, a GoPro camera and an IMU were set up on the deck and the vessel respectively. Figure 8 depicts the image captured by the GoPro camera.
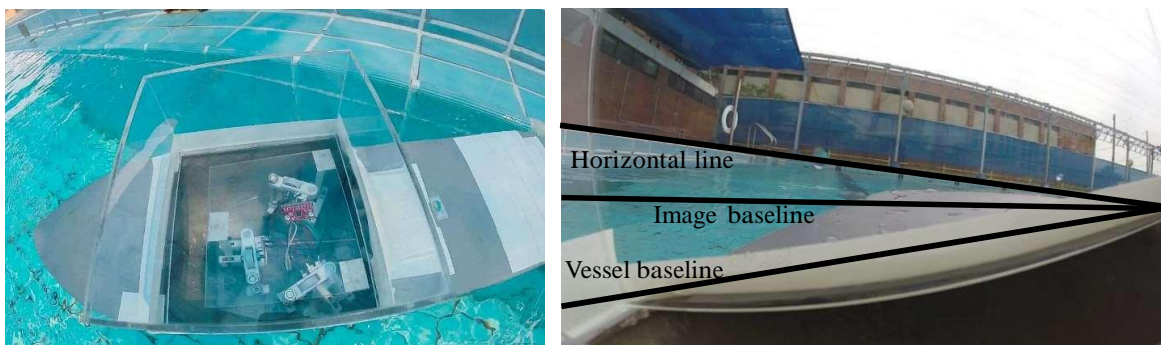

Figure 7. The scaled down self-balance system   Figure 8. Image captured by GoPro camera

The system performance is visible through the difference between image baseline and vessel baseline compared to the horizontal line. Figures 9 and 10 show the instant pitch and roll angle data gathered by the IMU with (blue curves) and without (orange curves) the control system when the vessel encounters external disturbances due to waves. Results of the field experiments clearly demonstrate the presented self-balance system works effectively in balance of the deck by counterbalancing external disturbances from the wave.
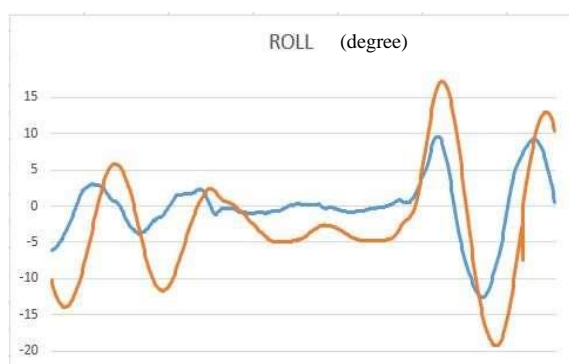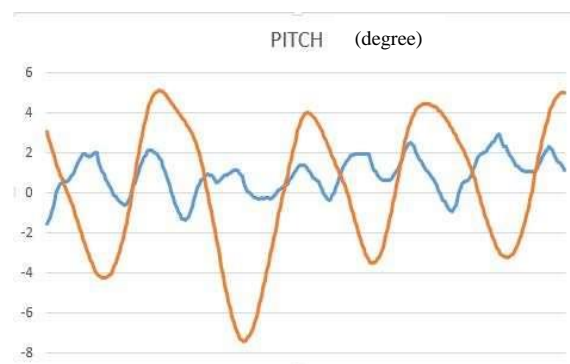

Figure 9. Roll angle information   Figure 10. Pitch angle information

4. Conclusion

Field experiments show the proposed self-balance system is able to counterbalance external disturbances from the wave; however, the system did not totally eliminate the disturbances in both pitch and roll directions, especially for large angle change as shown in figures 8 and 9. There are several aspects can take further into considerations:

- The operational range of the designed mechanism is limit to small displacement due to its nonlinear behavior at large displacement.
- The accuracy of the IMU is greatly degraded in the environment with noises.
- Different controllers can be discussed to improve the response of the system
- System frequency response needs to be conducted to analyze the stability of the control system with different types of external disturbances.

This project demonstrates how a self-balance system maintains level of the deck on a naval operation vehicle using modern technology and devices. The concept of the project can certainly be extended to other systems that are possible of encountering external disturbances.

Acknowledgments

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