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Balancing Control of a Single-wheel Robot Considering Power-efficiency and Gyroscopic Instability Suppression

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Abstract: The lateral-balancing problem of a single-wheel based robot system has been presented. The basic configuration of the system uses the gyroscopic effect which generates the yawing force as a control input. The friction combined with yawing force enables a robot system to maintain the lateral balance. Although this horizontal configuration gives a better pitching stability to the body system, enough friction and momentum must be guaranteed to perform the successful control task. To make a power-efficient system, in this paper, rolling force-based control configuration, namely the vertical configuration is proposed. Although this configuration has a major disadvantage in its pitching instability problem, efficient power consumption can be achieved. The pitch instability suppression is suggested to improve the balancing control algorithm performance. Experimental studies confirm that the power-consumption has been dramatically reduced and the correctness of instability suppression algorithm is properly verified.

Keywords: Gyroscopic instability suppression, power-efficiency, balancing control, GYROBO.

1. INTRODUCTION

CMG(Control Moment Gyro) has been used as an indirect robot actuator for balancing single-wheel mobile robots [1-5]. A single-wheel mobile robot, GYROBO has been developed at Chungnam National University [6, 7]. GYROBO performs a balance control using a gyroscopic effect.

There are two configurations of generating a gyroscopic force for a single wheel mobile robot depending upon the location of the gimbal system. The first concept of balancing control is based on the yawing force combined with the friction that generates the reactional force to the body system laterally. Therefore, ground conditions are one of the most important factors of the balancing control performance. To manipulate the gyroscopic torque using this horizontal configuration as shown in Fig. 1, high momentum gimbal system must be considered although this configuration has a disadvantage in the power efficiency yielding a pitch stability advantage.

A single-wheel robot system with yawing periodic motion generated by the gimbal system can generate parametric resonance to the orthogonal space of the system for balancing as well [6, 7]. In the horizontal configuration, the parametric resonances occur in both pitch and roll direction while the friction works as a resonance absorber.

As an autonomous mobile robot system, a power system occupies a lot of space and increases the weight of the whole system. Another concept of balancing control of a single-wheel is to use the rolling motion for balancing since it has high power-efficiency and a large exploration bandwidth advantage.

Therefore, a gyroscopically rolling motion control method for balancing is a good alternative although this vertical configuration has a major weakness of pitch instability compared to the first concept.

In this paper, the balancing performance of a single-wheel robot system considering the pitching instability is presented. To suppress the instability resonance, the offset compensation method is used by adding offset values to the reference of the PD controller. Then, the offset values according to both the gimbal angle value and the control bandwidth value are chosen empirically.

Experimental studies are conducted to verify the proposal of using the vertical configuration to balance the robot system.

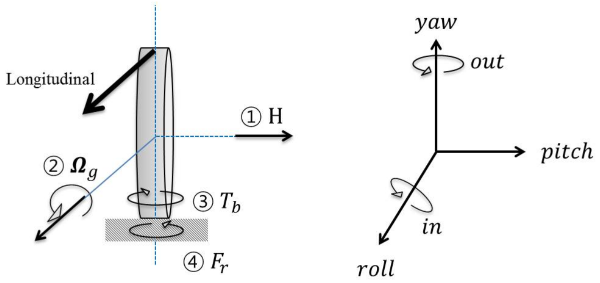
2. PRINCIPLES OF BALANCING

2.1 Previous Horizontal Concept

As the horizontal configuration, the yawing motion combined with the friction is shown in Fig. 1. H is the angular momentum of the flywheel, Ω_g is the flip motion which is the control input, T_b is the induced gyroscopic torque which is the control output, and F_r is the friction force of the ground system.

The reaction force by the friction generates the lateral force. Without friction, the robot rotates around the vertical axis of the robot system. To generate the body motion physically, the enough friction is required in the vertical configuration. The frictional force is dependent upon the body weight.

When the yawing force is over the frictional limitation, the residual yawing force generates a body motion. This means that the mechanism of generating high torque is required in the horizontal configuration since it has an advantage in the pitching stability.



(a) (b)

Fig. 1 The first concept of balancing control: (a) the horizontal concept, (b) input and output

The leaned gimbal generates a body force having two vectors as shown in Fig. 1 (b). The pithing vector component of the whole body force generates the pitching directional instability of the robot system. The yawing motion of the body system reduces the pitching motion effectively. Therefore, this concept of the balancing control has an advantage in the pitching stability.

Fig. 2 shows the previous system using the horizontal configuration.

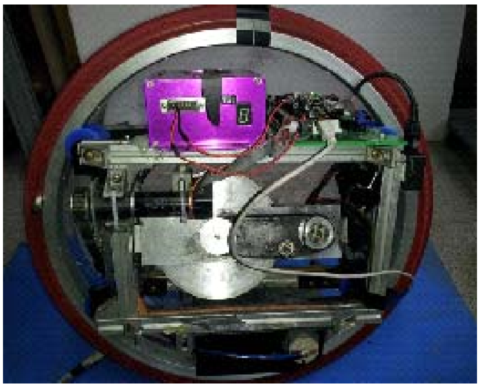


Fig. 2 Previous horizontal design

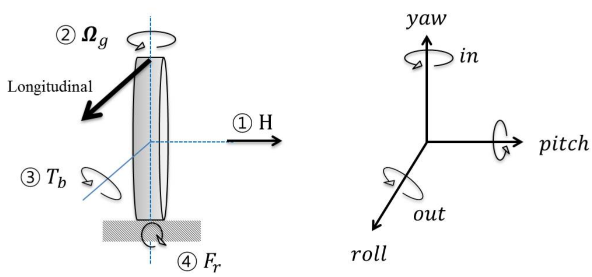
2.2 Proposed Vertical Concept

The second concept of the balancing control strategy is the vertical configuration as shown in Fig. 3. In the vertical configuration, the friction magnitude is dramatically diminished when compared to that of the horizontal configuration depicted as in Fig. 1 (a).

The vertical configuration has an advantage in the low power consumption to achieve the same gyroscopic effect of the body system compared with the horizontal configuration.

However, when the pitching vector component is more increased by the rotated gimbal state, there is not enough frictional force to reduce its unstable motion of the robot system. This feature becomes a disadvantage of the vertical configuration.

For the vertical configuration, the input is given in the yaw direction and the output is generated in the roll direction, which is the same direction as a gyroscopically induced force as shown in Fig. 3 (b).



(a) (b)

Fig. 3 The second concept of balancing control: (a) the vertical concept, (b) input and output

Fig. 4 shows the single-wheel mobile robot having the vertical configuration. We clearly see the different configuration between the horizontal and the vertical configuration. Different gimbal configuration yields different input and output configurations. The proposed configuration is tested for the balancing performance of the GYROBO.

Fig. 4 Proposed vertical design

3. CONTROL SCHEMES

3.1 PD Control

There are no direct actuators about the pitch axis in this system. However, the gyroscopically induced roll motion has a great effect on the motion of the pitch. A roll motion's parameter as a periodic lateral oscillation may generate the resonance at the pitch direction like the swing motion of the inverted pendulum having a spring.

To investigate this problem, the lateral balancing controller with a PD control algorithm is designed as shown in Fig. 5. The lateral attitude of the robot system can be monitored by the AHRS(Attitude and Heading Reference System) sensor system. Both the angle and the rate of the rolling motion are measured at every 1 *ms* from the sensor system.

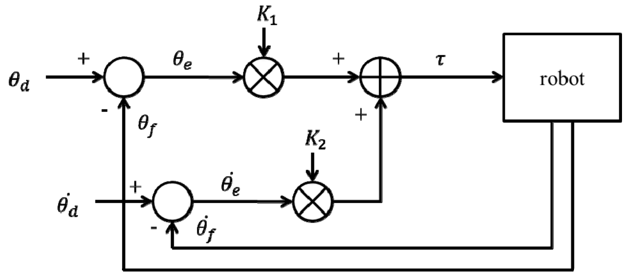


Fig. 5 PD control block diagram

The input torque is given as

$$\tau = K_1\theta_e + K_2\dot{\theta}_e \tag{1}$$

where θ_e is the balancing angle error, K_1 and K_2 are controller gains.

3.2 Proposed Control Scheme

Although the PD control method is simple, the robot falls down due to the resonance as time goes. As a solution of the problem, the offset update algorithm is proposed as shown in Fig. 6.

This algorithm includes a gimbal angle feedback. The algorithm updates the offset value every control period. The evaluated offset value from this algorithm is added to the reference value.

Then the overall offset equation is given as

$$\theta_{off} = A_{offset}\,\mathbf{sin}(2\pi\frac{gimbal\_position}{35000}) + L_{offset} \tag{2}$$

where A_{offset} can be calculated by considering the rolling bandwidth of the body system and L_{offset} values are determined by experiments.

A_{offset} can be calculated as

$$A_{offset} = \frac{gimbal\_angle}{2\pi} \times rolling\_bandwidth \tag{3}$$

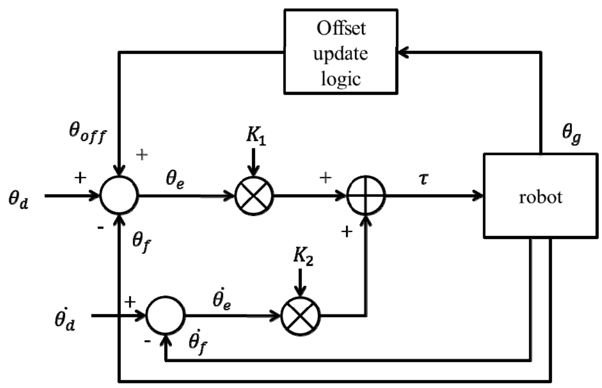


Fig. 6 Proposed control block diagram

4. EXPERIMENTAL STUDIES

4.1 Experimental setup

Fig. 7 shows the experimental setup for the balancing control performance. After steadily increasing the speed of the flywheel nearby 3000 RPM, the balance control performance is inspected. The values of the pitching instability are measured by the sensor system.

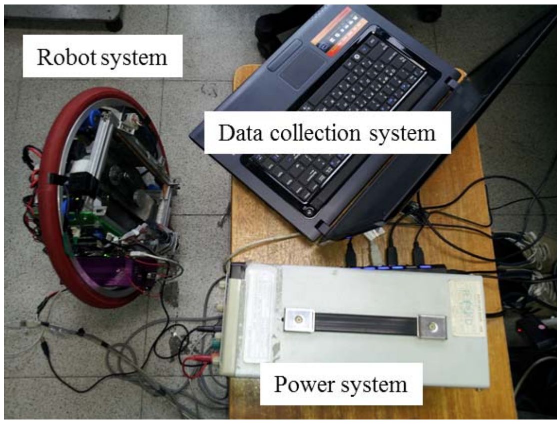


Fig. 7 Experimental setup

4.2 PD Control

For the PD controller gains, K_1 is 323.91304 and K_2 is 0.05284 for the experimental studies. Fig. 8 shows the roll angle performance. After 35 seconds of lateral balancing success, the robot falls down. The balancing angle starts oscillation around after 5 seconds. The oscillation gradually becomes large and finally the robot falls down.

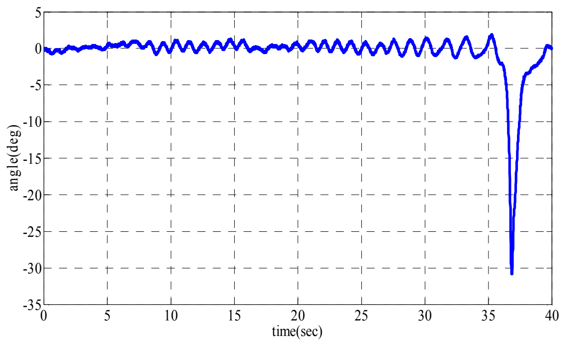


Fig. 8 Roll angle performance of PD control

4.3 Proposed Control

To remedy this problem, the compensation method of using equation (2) and (3) are used to compensate for the asymmetry of the system. The offset angle values are generated by those equations and added to the reference angle. It turns out that the rolling bandwidth is 4 degrees in this system which is smaller than that of the horizontal configuration.

The values of A_{offset} are heuristically found. Those values used in the experimental studies are listed in Table 1.

Table 1. Values of A_{offset}

A_{offset} / Gimbal area	Values
0~10 degrees	0.1
10~20 degrees	0.2
20~30 degrees	0.3
30~40 degrees	0.4
40~50 degrees	0.5

From the experiment, the roll angle is properly limited within a bandwidth. At the same time, the pitch control performance is also limited within a control boundary. Fig. 9 shows the roll angle performance of the proposed vertical configuration.

The robot maintains balance without falling down. We also note that the power consumption of the vertical configuration is less than 30 Watt compared with that of the horizontal configuration.

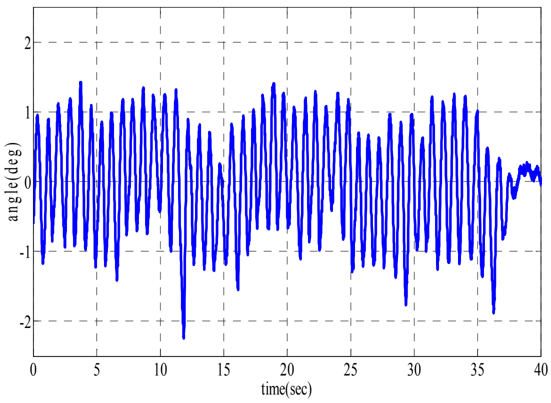


Fig. 9 Roll angle performance

5. CONCLUSION

In this paper, the lateral balancing problem considering the power-efficiency of single-wheeled robot system was addressed. Although the power consumption is dramatically improved in the vertical configuration, the gyroscopically induced instability should be considered. The offset values are calculated and obtained from both the gimbal angle position and the system analysis result. Experimental studies showed that the balancing performance has been improved. The continuous offset determined by the proposed method can avoid the fluctuation difficulty.

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