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Awakening Strategies from a Sleeping Mode to a Balancing Mode for a Sphere Robot

Sang Deok Lee and Seul Jung*

Abstract: This paper presents the strategy of awakening a sphere robot from a sleep mode to a balancing mode. The sphere robot is designed on the basis of a single-wheel robot covered with two hemispheres to have the sphere shape with casters to maintain the sleep mode at a specific angle. The sleep angle has been empirically found to be 16 degrees for enabling the sphere robot to be upright position. The gyroscopic force is controlled to perform the awakening strategy of the robot system. Firstly, the key design features such as angular momentum, agility, and controllable bandwidth are investigated to identify three phases such as triggering, stumbling, and stabilizing for the awakening strategy. Secondly, the sphere robot is modeled as an inverted stick and the phase portrait of the model is analyzed. Thirdly, a control law with a compensation algorithm is proposed to enhance the stabilizing performance. Finally, the proposed awakening strategy is verified through experimental studies.

Keywords: Awakening strategy, one-wheel mobile robot, self-balancing, sphere robot.

1. INTRODUCTON

Balancing techniques for mobile robot systems are quite challenging and demanded as the number of wheels of robots is minimized. Segway is one of the two-wheel vehicles that have attracted researchers' attention for a long time since the system requires challenging efforts in the aspects of design and control [1, 2]. Many different two-wheel mobile robots have been developed and presented in the literature [3–8].

More challengingly, researchers' desire leads to develop single-wheel mobile robots [9]. Compared to two-wheel robots, a single-wheel robot has advantages of more agile movements. For an instance, a single-wheel can immediately change the heading angle without detouring. In other hands, a single-wheel robot has a difficulty in implementation and control since the robot of a single-wheel design can fall down in any direction. Balancing performance should be guaranteed by the indirect actuation such as an inertial force or a gyroscopic force due to the structure of the single-wheel design. A gyroscopically actuated sphere robot may have advantages of navigation in the desert, water or space, where the terrain is not hard enough for wheels to stand up.

Reaction wheels have been used to generate the inertial force in the rotational direction for balancing a single-wheel robot [10, 11]. To achieve the same purpose of balancing, the gyroscopic force has been also utilized [12]. Gyrover has been developed for exploring planets in the universe and its performances have been well demonstrated in the literature [13, 14].

In the previous research, a single wheel robot, GYROBO has been developed as an autonomous vehicle for the outdoor exploration. Successful balancing control and navigation of GYROBO have been demonstrated [15]. The single wheel mobile robot systems are controlled by the gyroscopic effect [16, 17] and by the ducted fans [18]. The main purpose of those actuations is to maintain balancing with the help of a human at the beginning.

Therefore, it is necessary for the robot to stand up by itself without the human help. This paper focuses on this issue. A single-wheel robot should be autonomous to navigate its terrain to perform tasks. Autonomous navigation of the single-wheel robot requires many necessary technologies such as a self-charging power system, autonomous navigation algorithm, a self-monitoring system, and a self-moving mechanism. Among them, the self-erection mechanism allows the robot to move autonomously and it is the basic concept to be considered.

Therefore, our concern here is to investigate how the robot stands up automatically from the sleeping mode to the balancing mode and how the robot maintains balancing more stably as shown in Fig. 1. For the convenience, the robot is designed to be a sphere which has two hemi-

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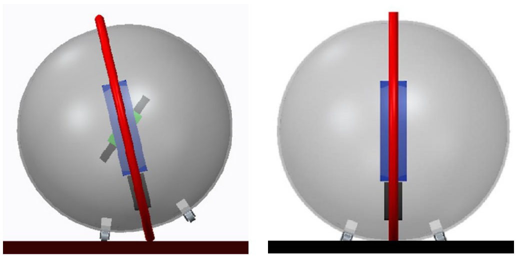
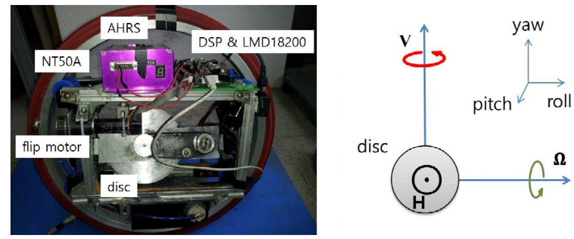
Sangdeok Lee and Seul Jung are with the Intelligent Systems and Emotional Engineering(ISEE) Laboratory, Department of Mechatronics Engineering, Chungnam National University, 99 Daehak-ro, Yuseong-gu, Daejeon 34134, Korea (e-mails: {sdcon.lee, jungs}@cnu.ac.kr).
* Corresponding author.



(a) Sleep mode. (b) Balancing mode.

Fig. 1. Awakening concept.



(a) GYROBO. (b) Gyroscopic effect.

Fig. 2. GYROBO.

spheres with casters to prevent the robot from falling down completely for easy erection. The casters will help the robot to stand up with ease by limiting the sleep angle to use the frictional force from the ground effectively. Ultimately, the sphere robot can have different stages between the sleep and the normal state for the efficient power consumption.

The paper is organized as follows: Firstly, the performance of the control moment gyroscope (CMG) is analyzed through the extensive experiments. The standing-up mechanism and control laws with a compensation algorithm are proposed. Simulation studies of the phase portraits for the inverted stick model are conducted to investigate the robustness. Finally, the proposed strategy is verified through empirical studies.

2. PROBLEM STATEMENT

2.1. Robot system configuration

CMG based one-wheel robot, GYROBO is shown in Fig. 2(a). The robot has three motors: a spin motor, a flip motor, and a drive motor. A spin and a flip motor are used for balancing and a drive motor for driving. Since the drive motor is simply controlled for driving, main control to the robot is the flip motor to rotate the gimbal system for inducing the gyroscopic force.

The robot uses an AHRS (attitude and heading reference system) sensor for detecting the lean angle of the body. The robot is controlled to maintain the desired lean angle, namely zero. The DSP is used as a main controller and controls the LMD18200 H-bridge circuit as a flip motor driver.

The robot uses the gyroscopic effect induced in the yaw axis to maintain balance. Fig. 2(b) shows the gyroscopic mechanism. The gyroscopic motion V is induced by the combination of the angular momentum H and the flip motion Ω. The flip motion combined with the spin motion generates the gyroscopic effect as shown in Fig. 2(b).

2.2. Problem statements

An autonomous balancing capability from the sleep mode is required for the one-wheel robot to operate autonomously in its terrain. The awakening strategy enables the one-wheel robot to be self-balancing. For the robot to have the self-balancing ability, control of the yawing motion can be one of feasible solutions. Adding the casters to the hemispheres helps the robot to erect with ease by increasing the friction force.

Then the question of how to decide the position of the caster is raised since the solution is dependent on various factors such as ground condition, the specification of the caster, the hemisphere, and so on. Here control of CMG plays a key role for the problem. The characterization of the CMG is investigated and the performance of the CMG is evaluated.

Next question is how to stabilize the robot by maintaining balance. The balancing control concept of the inverted pendulum model can be used to solve this problem. Since the gyroscopic force of the robot has two vectors such as a yawing force and a pitching force, the robot can be modelled as an inverted stick with vertical oscillation. The rolling axis can be modelled as a pendulum and the pitching motion as the vertical oscillation.

3. GYROBO SYSTEM

3.1. System analysis

The system is analyzed through extensive experimental studies. Firstly, we make the flywheel rotate at a constant speed 5,700 RPM. A flywheel has 2.1kg weight and a 0.075 m radius. The inertia of the flywheel can be calculated as

$$I = \frac{1}{2}mr^2 = \frac{1}{2} \times 2.1 \times 0.075^2 = 0.005906(\mathrm{Kgm}^2), \tag{1}$$

where m is 2.1 kg and r is 0.075 m.

When the flywheel rotates at a constant speed of ω, the magnitude of the angular momentum becomes

$$H = I\omega = 0.005906 \times 597 = 3.525(\mathrm{Nms}). \tag{2}$$

Combining (2) with the flip motion Ω can generate the gyroscopic effect. Therefore, the angular momentum has a constant value and the flip motion can be used to manipulate the gyroscopic force.

The general description of the induced torque by the gyroscopic effect is

$$T = H \times \Omega, \tag{3}$$

where T is the gyroscopic torque.

However, the equation shows the relation between the velocity and the torque. In practice, it is not easy to manipulate the torque directly.

Gyroscopic motion has the following relationship

$$V \propto \frac{1}{H}, \tag{4}$$

$$V \propto \Omega. \tag{5}$$

Therefore, we can assume the velocity relation as

$$V = \alpha \frac{1}{H} \Omega (-\infty < \alpha < \infty). \tag{6}$$

Equation (6) describes the motion to motion relation. The specific case of $\alpha = 1$ is considered to use the gyroscopic effect more easily.

Ω can be obtained from the measurement through the experiment. We use LMD18200 device as a flip motor driver of which input voltage can be set by PWM (Pulse Widths Modulation) method. When 100% duty is applied to the device, the agility of the flip motor can be confirmed. In the measurement, the pulley and gear of the flip motor is considered. Ω is measured as 4.371 rad/s. As a result, the gyroscopic motion is estimated from (6) such that V becomes 1.24 rad/s.

In the robot system, although yawing and pitching motions are available by the gyroscopic actuation, how to generate the roll motion of the robot is still a query. To remedy this query, the reactional force of the yawing motion using the caster-equipped hemisphere is utilized. The value of the frictional force plays the key role to the concept of awakening strategies of dealing with the rolling motion.

The conceptual sequence of awakening the robot from the sleeping mode has four steps as shown in Fig. 3. Firstly, the flip motion of the flywheel is generated. The gyroscopic force then can be induced in the yawing direction of the robot body. Since the caster prevents the body from rotating around the yaw axis, the reactional force can generate a rolling motion of the robot system.

If the ground does not provide sufficient frictional force, slip will occur. In addition, the initial tilt angle of the given system must be selected with regard to the gyroscopic torque of the mounted CMG. In the actual experiment, a friction tape can be used to maximize the frictional force. Under the frictional condition, the angle of the casters to the sphere is identified experimentally.

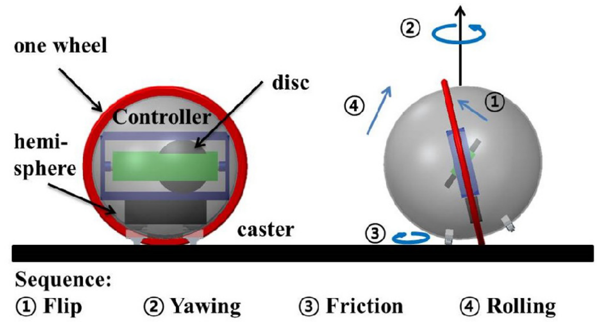


Fig. 3. The concept of awakening strategies.

Table 1. The summary of control parameters.

Parameters	Values	Units
Flip motion agility	4.371	rad/s
Robot motion agility	1.24	rad/s
Angular Momentum	3.525	Nms
Stabilizing range	-5.5∼5.5	degrees
Stumbling threshold angle	-5.5, 5.5	degrees
Triggering threshold angle	-11, 11	degrees

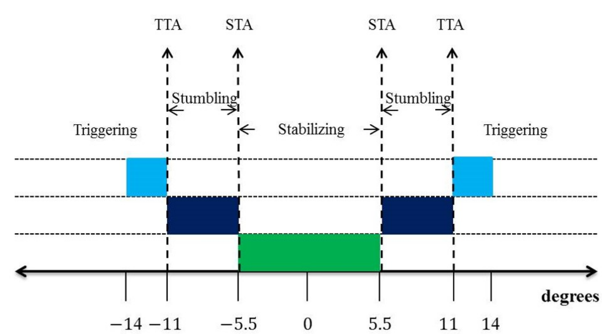


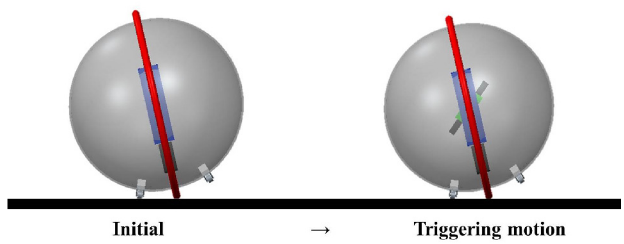
Fig. 4. Proposed angles for awakening control.

As the next step, the agility of the robot is estimated through the extensive experiment. The falling down motion of the robot is investigated. In the experiment, the value of the controllable angle is found to be about 11 degrees. Considering the abrupt change of directions of the robot, the control parameters found empirically are listed in Table 1.

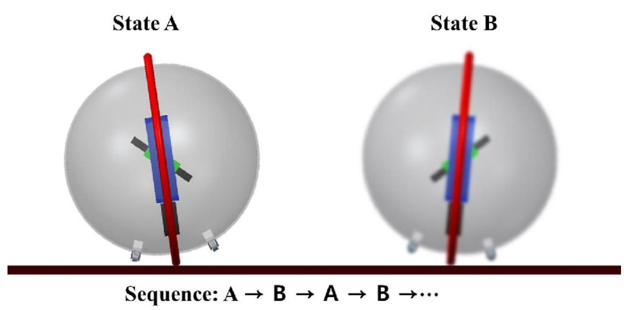
3.2. Concept of awakening strategy

Firstly, the identification of the leaning angle at rest is performed by locating the casters on the hemispheres nearby 16 degrees. The designed strategies from the sleeping mode to the standing-up motion about angles are shown in Fig. 4.

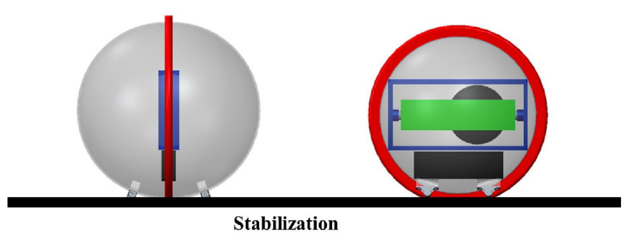
The strategy can be divided into three phases. First, the triggering motion of the robot is applied. The repeated flip motion generates the triggering motion and the sensor detects the roll angle of the robot. In the second step, the



(a) Triggering.



(b) Stumbling.



(c) Stabilizing.

Fig. 5. Awakening strategies.

robot goes to the stumbling motion state before entering into the stabilizing state. Finally, the stabilizing motion enables the robot to stand upright.

Fig. 5 shows the figures of the proposed strategies with respect to lean angles.

4. CONTROL SCHEMES

4.1. Manipulation of gyroscopic force

The gyroscopic actuation of the robot has two vectors: the yawing and the pitching vectors. The yawing force can be considered as an intrinsic actuation of the robot system. Therefore, the decoupling method can be used as follows:

$$F_G = F_Y + F_P, \tag{7}$$

where F_G is the total force of the gyroscopic effect, F_Y is the lateral force, and F_P is the vertical force. The lateral law using the PD control method can be described as

$$F_Y = K_p \theta_e + K_d \dot{\theta}_e, \tag{8}$$

where K_p, K_d are control gains and $\theta_e = \theta_d - \theta_s$.

The vertical dynamics of the inverted stick model system with oscillation is given as

$$\frac{1}{6} ML\ddot{\theta} + (-Mg + Mp\omega^2 \cos\omega t)\sin\theta = F_p, \tag{9}$$

where θ is the lateral angle, ω is the angular velocity, M is the mass, L is the length, g is the gravity acceleration, F_p is the input force, and p is the magnitude of vertical oscillation.

Rearranging (9) yields

$$\ddot{\theta} + \left(-\frac{6g}{L} + \frac{6}{L} p\omega^2 \cos\omega t\right)\sin\theta = \frac{6}{ML} F_p. \tag{10}$$

Rewriting (10) becomes

$$\frac{d^2\theta}{d\tau^2} + \left(-\frac{\omega_0^2}{\omega^2} + \frac{6}{L} p\cos\omega t\right)\theta = \frac{6}{ML\omega^2} F_p, \tag{11}$$

where $\omega_0^2 = 6g/L$.

Equation (11) is known as the Mathieu equation of parametric oscillation problems when $\omega = \omega_0$ [19–21].

$$\ddot{\theta} + (\alpha + \beta\cos\omega t)\theta = \frac{6}{ML\omega_0^2} F_p = \frac{1}{Mg} F_p, \tag{12}$$

where $\alpha = -\left(\omega_0^2/\omega^2\right)$, $\beta = (6p/L)$.

The right side of (12) shows the vertical input force. The dynamics of the robot with no input force can be shown as

$$\ddot{\theta}_s + (\alpha + \beta_s \cos\omega t)\theta_s = 0. \tag{13}$$

When the vertical force is applied to the robot system, the force makes a robot having a certain state such as $(\ddot{\theta}_s, \dot{\theta}_s, \theta_s, \beta_s)$.

In fact, the vertical force of the gyroscopic effect can be considered as a disturbance. Moreover, it can be combined with the lateral motion and results in generating a parametric oscillation. Therefore, it is important to analyze the dynamic property of (13) a priori. The phase trajectory is used for analyzing the stabilization problem.

Firstly, the condition of oscillation-free state when β_s is zero is considered. Then, we assume the estimated state values of the robot as $\theta_s = 0$ degrees and $\dot{\theta}_s = 0.05$ rad/s.

However, the instability is increased when β_s is not zero. To compensate for the instability, a novel offset compensation method is proposed as follows:

$$\ddot{\theta}_s + (\alpha + \beta_s \cos\omega t)(\theta_s - A\sin\theta_s) = 0, \tag{14}$$

where A is a magnitude.

The performance of a nonlinear offset function is simulated by plotting the phase trajectory whether the proposed function can suppress the oscillation or not.

Fig. 6 shows the simulation results. Fig. 6(a) indicates the trajectory movement when the vertical oscillation is

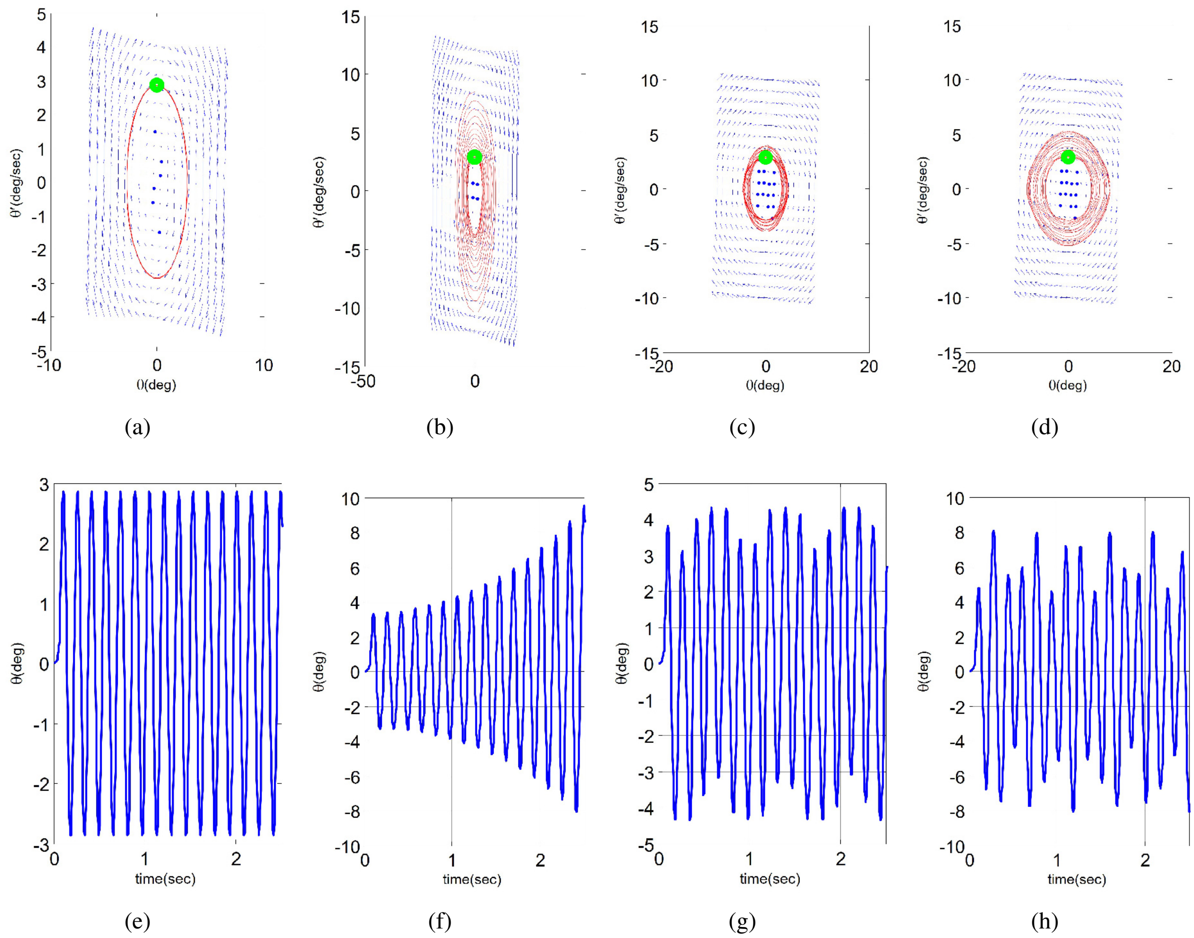


Fig. 6. Stability analysis: (a) $M = 2.1$ kg, $L = 0.5$ m, $p = 0$ $A = 0$, (b) $M = 2.1$ kg, $L = 0.5$ m, $p = 0.35$ $A = 0$, (c) $M = 2.1$ kg, $L = 0.5$ m, $p = 0.35$ $A = 0.3$, (d) $M = 2.1$ kg, $L = 0.5$ m, $p = 0$ $A = 0.6$, (e) angle plot of (a), (f) angle plot of (b), (g) angle plot of (c), (h) angle plot of (d).

zero. If we use zero rate, the phase trajectory shows equilibrium states. Fig. 6(e) shows the time plot of the angle which is stable. Fig. 6(b) shows the state when the amplitude of the vertical oscillation is 35 mm. The phase diverges and the corresponding angle plot goes unstable as shown in Fig. 6(f). Fig. 6(c) shows the phase plot when $A = 0.3$. The addition of the compensation signal makes the system stable. The corresponding angle plot is shown in Fig. 6(g) and the angle is bounded. Figs. 6(d) and (h) show the effect of the offset magnitude. When the offset magnitude is not selected properly, the performance can be deteriorated.

Therefore, the offset magnitude should be properly selected by considering the vertical oscillation property.

4.2. Control scheme

The decoupled control law of the gyroscopic force can be formulated as follows: Firstly, the lateral control for the standing-up motion is designed through a linear PD-control method given in (8). A nonlinear offset is added to the controller for enhancing the control performance. Therefore, the control law becomes

$$F_Y = K_p(\theta_d - \theta_s - A\sin(\theta_s)) + K_d\dot{\theta}_e, \quad (15)$$

where K_p, K_d are controller gains.

The control block diagram is shown in Fig. 7. The feedback signals such as the angle and the angular velocity of the roll angle are periodically fed back and the control routine can be updated at an interval of 10 ms.

5. EXPERIMENTAL STUDIES

5.1. Experimental setup

GYROBO with hemisphere covers is shown in Fig. 8(a). Initially the robot is at rest on the ground as shown in Fig. 8(b). The initial leaning angle of the sleeping robot is measured to be 16.016 degrees due to the structure of the robot as shown in Fig. 8(b). Casters in Fig. 8(c) support the body by enabling the robot to maintain within a specific angle. The angle has been found

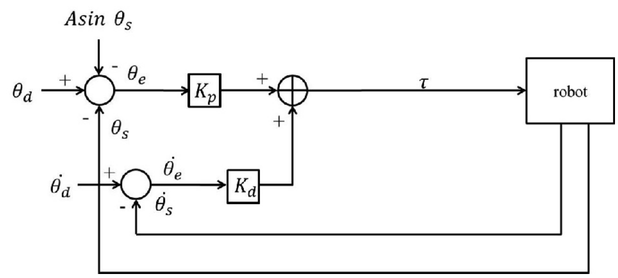


Fig. 7. Control block diagram.

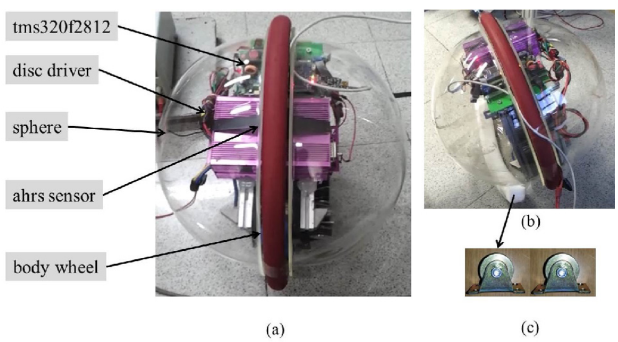


Fig. 8. Experimental setup. (a) GYROBO at standing, (b) GYROBO at rest, and (c) Casters.

by empirical studies for the robot to have enough force to erect.

5.2. Control without compensation

When the system is controlled without any compensation, Fig. 9 shows the diverging angles of GYROBO in roll and pitch direction. When the compensating control was not applied, experimental results are quite similar to the simulation results shown in Fig. 6(f). Therefore, for the awakening experiment, compensation control in Fig. 7 is applied.

5.3. Awakening experiment

After the triggering control is completed, the control proceeds to the balancing control stage with the help of the frictional force with the ground. The required gyroscopic torque for the balancing control is smaller than that of the triggering control. This has been accomplished by adjusting the proportional gain value.

Gain scheduling for awakening strategies was used since the different forces are required for different conditions of stages. As a scheduled gain, different gains are found for triggering, stumbling, and stabilizing. Gains are listed in Table 2. $K_d = 0.1$ and A is 0.3 are used for the experiment.

Fig. 10 shows the actual demonstration of awakening process of GYROBO for 18 seconds. Initially, the robot is at the sleeping mode for 5 seconds. The robot is triggered several times to induce the oscillation to the body with

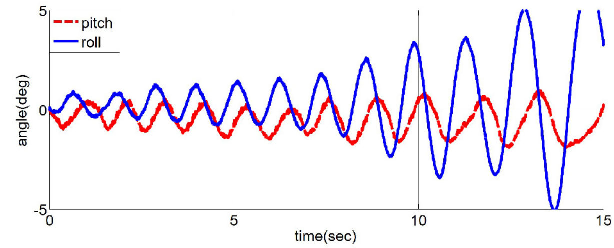


Fig. 9. Experimental result for the coupled effect of GYROBO.

Table 2. Gain scheduling values.

Motions	Parameters	Values
Triggering	K_p	4
	Initial angle	16.016
	Desired angle	11
Stumbling	K_p	3
	Desired angle	5.5
Stabilizing	K_p	2
	Desired angle	0

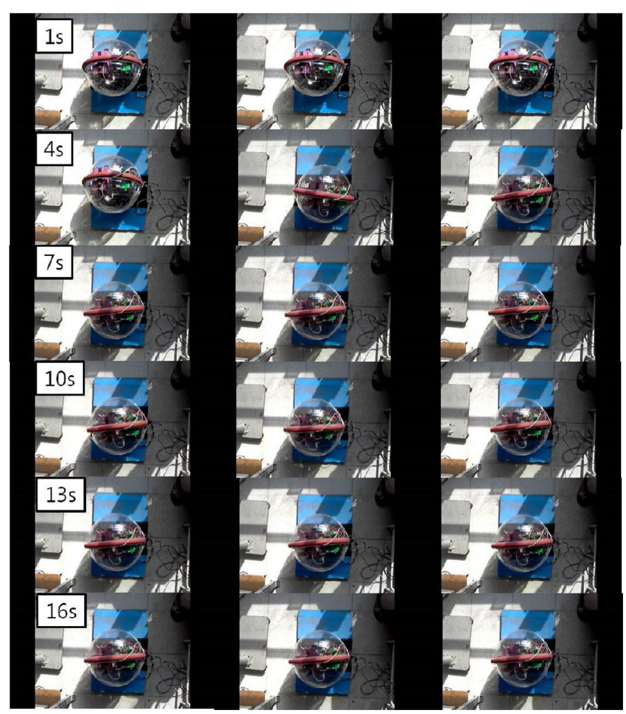
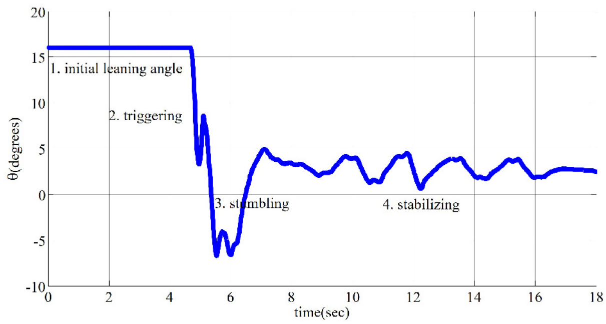


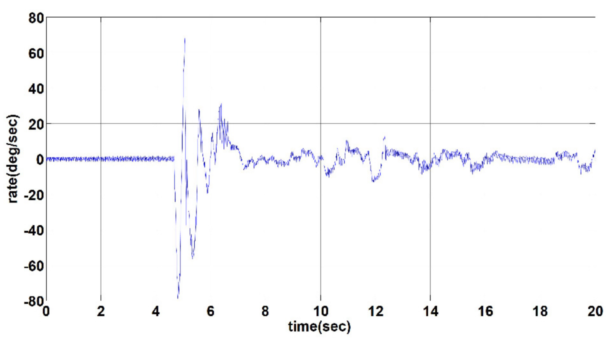
Fig. 10. Awakening strategy demonstration.

respect to the casters against the ground. After several oscillations, the robot finally maintains balance at around 7 seconds.

The corresponding angle plot demonstrating the awakening strategies is shown in Fig. 11(a). Initially, the triggering algorithm is applied to wake the robot from the sleeping mode with the initial angle of 11 degrees. The



(a) Lean angle.



(b) Lean angle rate.

Fig. 11. Erecting performance of Fig. 10.

robot then starts the stumbling motion where the robot moves its attitude within ±5 degrees. Finally, the stabilizing motion is applied to maintain balance after 12 seconds. The balancing angle offset after the stabilization phase appears due to the asymmetry of the robot, where the center of mass is not located on the center of the body. Fig. 11(b) shows the lean angle rate.

The awakening process is strongly dependent upon two agilities, a flip motion agility and a robot motion agility. The robot motion agility is also dependent on the lean angle, contact friction state, and so on. The expected agility of the robot motion was 1.24 (rad/s) or 71 (degrees/s) and the experimental result was 80 (degrees/s) as shown in Fig. 11(b). Therefore, the awakening strategy is feasible.

6. CONCLUSIONS

The strategy of awakening a one-wheel robot for autonomous navigation is presented. The standing-up control method has been proposed by the experimental studies. The gyroscopic effect as the motion's relationship is characterized and analyzed. The control law considering the desired motion, scheduled gains, and vertical compensation is designed and applied to the system. The analysis of the phase trajectory has been simulated before applying the control law to the real robot system. The feasibility of the proposed strategies has been confirmed through the empirical studies. The robot was successful to maintain balance from the sleeping mode through the proposed strategy.

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Sang-Deok Lee received his B.S. and M. S. degrees in Electronics Engineering from Cheonbuk National University, in 1998 and 2003, respectively. He joined LG Precision and Samsung Heavy Industries from 1998 to 2000 and from 2003 to 2014, respectively. He is currently a Ph.D. candidate in Department of Mechatronics Engineering at Chungnam National University. His research interests are Mechatronic system identification and control.

Seul Jung received the B.S. degree in Electrical and Computer Engineering from Wayne State University, Detroit, MI, USA in 1988, and the M.S. and Ph.D. degrees in Electrical and Computer Engineering from the University of California, Davis, in 1991 and 1996, respectively. In 1997, he joined the Department of Mechatronics Engineering, Chungnam National University, where he is presently a professor. His research interests include intelligent Mechatronics systems, intelligent robotic systems, mobile manipulators for home service applications, gyroscope applications, and robot education. He is a member of IEEE, ACA, ICROS, KROS, KIIS, KIEE, IEMEK, and IEEK.