Driving and Turning Control of a Single-Wheel Mobile Robot

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Abstract. This paper presents driving and balancing control of a single-wheel mobile robot system called the name of GYROBO. GYROBO utilizes a gyro effect to stabilize itself. Three actuators are used to perform driving and balancing tasks. After modification of hardware and relocation of materials inside the wheel housing of the previous GYROBO model, performances of trajectory following control as well as balancing control are improved. Linear controllers are used for both roll, pitch and yaw angle control. GYROBO is required to follow the specified trajectories commanded by a remote operator. Trajectories include a straight line and curved trajectories. Experimental studies of driving and turning control are conducted and its performances are demonstrated.

Keywords: single-wheel mobile robot, gyro effect, balancing, driving and turning control

1 Introduction

Research on mobile robots has been dominant in the field of robotic areas due to the increasing utilities of service robots. To function as a service robot, mobility is a fundamental capability for a robot to perform tasks.

Mobility of mobile robots becomes a challenging problem as the number of wheels is decreasing. The number of wheels determines three categories of mobile robots, a plane contact, a line contact and a point contact robot.

Surely, the majority of mobile robots having four wheels belong to the plane contact category. Mobile robots of the plane contact category have stable driving performance but have kinematics constraints as a nonholonomic system. One disadvantage is the limited maneuverability that allows wide turning so that applications in narrow space are not feasible.

Three-wheel mechanism can be used for the narrow space application since the robot forms a holonomic system structure of generating omnidirectional movements. Omni directional mobile robots are of use in indoor environment that does not require fast driving, but good maneuverability.

Two-wheel mobile robots are the category of a line contact that explores challenging mobility since balancing by two-wheel is difficulty and should be guaranteed. To maintain balancing in the heading direction, pitch angle control becomes important. Segway is one of successful commercialized two-wheel mobile robots [1]. Research on two-wheel mobile robots has been enormously increased and demonstrated challenging control performances [2-6].

The last category is a single-wheel robot that makes a point contact on the ground. Control of a single-wheel mobile robot is quite challenging because it can fall down in any directions with ease. Thus, control of a single-wheel robot is the most difficult among aforementioned categories.

A single-wheel robot balances itself by gyro effects induced from a fast rotating flywheel as shown in Fig.1 [7]. Gyrover has been a dominant model to present a single-wheel mobile robot for many years with several models [8-10]. A single sphere type mobile robot has been presented to demonstrate balancing and navigation [11].

In the previous research, GYROBO I has been presented and demonstrated its balancing performance, but an oscillatory behavior has been observed [12]. To suppress the oscillation, several design modifications of GYROBO I have been made to improve balancing performances.

All of hardware should be packed within a single wheel to make the center of mass be located on the horizontal and vertical axis of the wheel. Locating materials to make the system be symmetrical in horizontal axis becomes an important factor for successful balancing. Therefore, modification of a body structure has been done by relocating materials inside the wheel.

In this paper, experimental studies of following straight and curved trajectories are performed. The trajectories are given for GYROBO to follow through wireless communication from a remote operator.

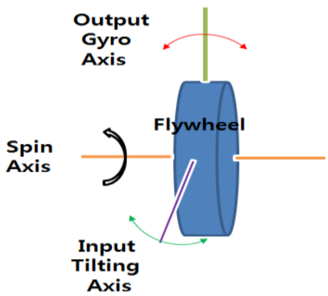

Fig. 1 Concept of gyro effect of a flywheel

2 GYROBO Modeling

The structure of GYROBO is a disc-typed mobile robot. Fig. 2 shows the kinematic configuration of GYROBO. Variables are listed in Table 1.

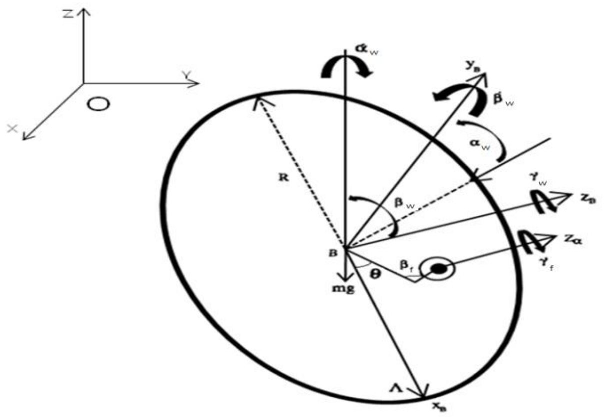

Fig. 2 Model of GYROBO

Table 1. Definition of Variables

X, Y, Z	Position coordinate frame
α_w, β_w, γ_w	Precession, Lean, Rolling Angle of the wheel
β_f, γ_f	Tilt angle and spin angle of the flywheel
R	Radius of the wheel
m	Total mass
u_d, u_t	Torque of drive motor and tilt motor
μ_α	Friction coefficient in yaw direction
I_x, I_y, I_z	Moment of Inertia of Body
I_{xf}, I_{yf}, I_{zf}	Moment of Inertia of Flywheel
S_x, C_x	Sin(x), Cos(x)
$S_{x,y}$, $C_{x,y}$	Sin(x+y), Cos(x+y)

There are two wheels to be controlled. One is a system body that rolls and another is the flywheel to generate gyro motions. Rotation variables or the body are $\alpha_w, \beta_w, \gamma_w$ which are roll, yaw, and pitch angle, respectively. Variables for the flywheel are β_f, γ_f which are tilt and spin angles, respectively. Therefore, controlling the tilt angle of the flywheel regulates α_w, β_w of the GYROBO.

Since GYROBO moves on the plane, the Cartesian velocity can be described as below.

$$\begin{cases} \dot{X} = R(\dot{\gamma}_g C_\alpha + \dot{\alpha} C_\alpha C_\beta - \dot{\beta} S_\alpha S_\beta) \\ \dot{Y} = R(\dot{\gamma}_g S_\alpha + \dot{\alpha} S_\alpha C_\beta + \dot{\beta} C_\alpha S_\beta) \end{cases} \tag{1}$$

The dynamic equation can be represented as below in [10].

$$M(q)\ddot{q} = F(q,\dot{q}) + Bu \tag{2}$$

where *M* is the inertia matrix, *B* is the input transformation matrix, *u* is the control input vector, $q = [\alpha_w, \beta_w, \gamma_w]^T$, and $F = [F_1, F_2, F_3]^T$. The closed loop feedback control input is $u = [u_d u_t]^T$.

Although the detailed dynamic equation is given in [10], here we use a non-model based control method. It is true that modelling a single wheeled system is quite difficult and modelled parameters do not often match with those of a real system.

3 Control Scheme

Here we assume that the flywheel rotates at the high constant speed. Then the tilting angle β_f of the flywheel is a key variable to generate control input for GYROBO to balance as in Fig. 1. Angles of GYROBO are a precession (yaw) angle, α_w , a lean (roll) angle, β_w , and a rolling (pitch) angle, γ_w . The rolling angle is simply controlled by a driving DC motor. The precession and lean angles are controlled by the force induced from the cross product of rotational forces of the spin axis and the titling axis of the flywheel. Thus, the control input variable of GYROBO is the tilt angle, β_f of the flywheel.

Control inputs for the roll and yaw angle control are designed separately as a PD control method.

$$u_\beta = k_{p\beta}(\beta_{dw} - \beta_w) + k_{d\beta}(\dot{\beta}_{dw} - \dot{\beta}_w) \tag{3}$$

$$u_\alpha = k_{p\beta}(\alpha_{dw} - \alpha_w) + k_{d\alpha}(\dot{\alpha}_{dw} - \dot{\alpha}_w) \tag{4}$$

where $k_{p\beta}, k_{d\beta}$ are PD controller gains for the roll angle control and $k_{p\alpha}, k_{d\alpha}$ are PD controller gains for the yaw angle control.

The control input to the tilt angle of the flywheel is the sum of two control output signals given in (3) and (4).

$$u_t = u_\beta + u_\alpha \tag{5}$$

Fig. 3 shows the control block diagram for controlling angles of GYROBO. There are other control input signals to GYROBO, the driving torque u_d to the wheel and the spin torque u_γ to the flywheel which form open loop control.

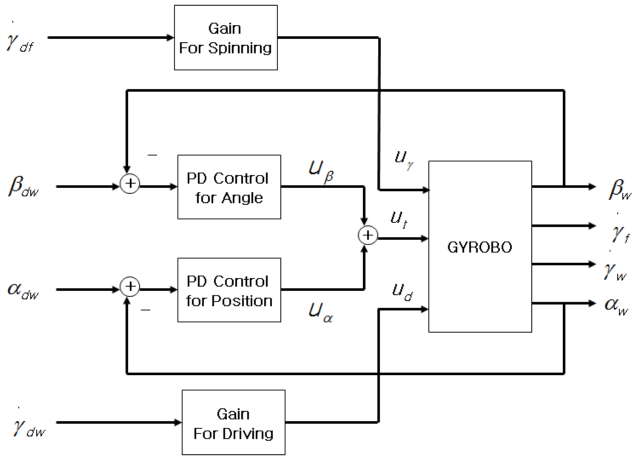

Fig. 3 Control block diagram of driving control

4 GYROBO System

4.1 GYROBO design

Real implementation of GYROBO is shown in Fig. 4. Three actuators, a drive motor, a spin motor, and a tilt motor are used to generate three angular motions. A drive motor generates the motion of a pitch angle, and combination of a tilt motor and a spin motor generates roll and yaw motions. A drive motor actuates the wheel and a tilt and a spin motors actuates the flywheel. Sensors and control hardware are located on the center of the top. A battery is located at the bottom to lower the center of the gravity.

It has an outer and an inner wheel structure as shown in Fig. 4. The outer wheel is made of rubber and the inner wheel contains all hardware. The outer and the inner wheel are connected by several rollers.

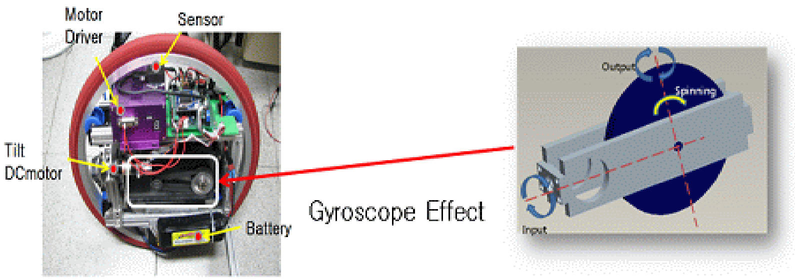

Fig. 4 Overall system structure of GYROBO

All of materials are packed inside the wheel which is the inner wheel. The diameter and the mass of the wheel are 0.45*m* and 11.2*kg*, respectively. The diameter and the mass of the flywheel are 0.15*m* and 2.1*kg*, respectively.

The most important concern for the design is the flywheel part which generates the gyro effects by rotating at high speed. High speed rotation of the flywheel produces vibration due to many reasons such as asymmetry of a flywheel body, nonlinearity from a timing belt, a loose spin axis, and loosely coupled parts. Vibration causes inaccurate sensing measurement which results in poor control performance and unstable balancing.

The drive motor rotates the wheel itself by friction force. At initial driving, slip may occur to drive the wheel. Since the drive motor generates driving motion, open loop control is applied.

The current system has three different sensors, a gyro, and an encoder. The gyro sensor can measure 3 axes angular motions.

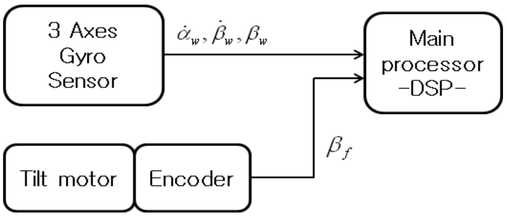

Fig. 5 Estimation of angle data

Fig. 5 shows the block diagram of obtaining data from the gyro sensor. Although the gyro sensor provides three axes data, two axes data are used since the yaw angle data are not reliable.

4.2. Hardware design

An overall control hardware structure is constructed as shown in Fig. 6. A DSP chip is used as a main controller for managing sensor signal processing, calculation of control algorithm, and PWM generation to motor drivers. Three sensors are used to detect motion of GYROBO. A three axes gyro sensor, a tilt sensor, and an encoder are used to detect the posture of the system. The gyro sensor is used for measuring a lean (roll) angle of the wheel and the tilt sensor is used for tilting the flywheel.

An operator uses a joystick to command the desired signals S_f, S_d to GYROBO through wireless communication remotely where the desired spin velocity is $S_f = \dot{\gamma}_{df}$ and the desired driving velocity $S_d = \dot{\gamma}_g$ as shown in Fig. 3.

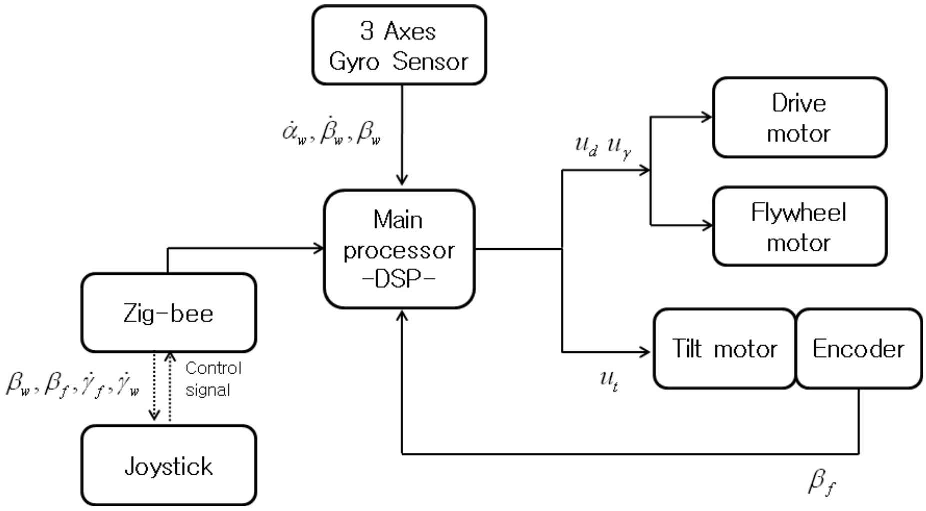

Fig. 6 Hardware structure

5. Experimental Results

5.1 Balancing control

Firstly, balancing control has been tested. Balancing control at one point of a single-wheel robot is more difficult than when it is moving forward. In this experiment, a roll angle is controlled only. At the beginning, GYROBO seems to make balancing, but it goes unstable. We notice that the tilting angle of the flywheel of GYROBO keeps increasing in one direction. This makes the system unstable.

In order to make the tilt angle converge, the angle should be maintained at around zero degree. Control inputs for the flywheel spin and the drive wheel are considered as open loop control. The tilting of the flywheel is only a closed loop control input. Therefore, leaning against one direction results in unstable balancing performance.

To remedy this problem, a yaw angle control loop is added as shown on the control block of Fig. 3. PD gains of roll and yaw angle control for experimental studies. PD gains are selected by trial and error experimental procedure for the better performances. The proportional gain of yaw control is set to zero because yaw angle data measured from the 3-axes gyro sensor are so noisy that they are not suitable to be used.

After adding the yaw angle control loop, balancing performances are much improved as shown in Fig. 7. Images are taken during the balancing control task from 0 to 12 seconds. Although there are small oscillatory movements in the yaw angle direction, GYROBO maintains balance well.

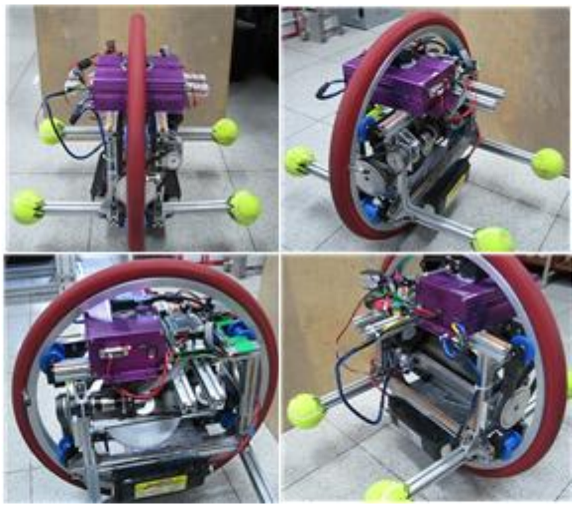

Fig. 7 Balancing demonstration of using roll and yaw angle control

5.2 Turning control

The next experiment is to turn the direction while balancing at one point. The desired roll command is given for GYROBO to make turn.

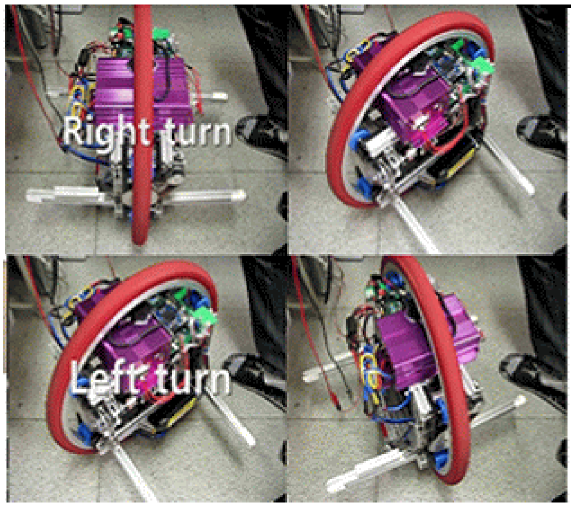

Fig. 8 Turning control demonstration

Fig. 8 shows the real demonstration of turning in the right and left direction. At the beginning, GYROBO tries to make balancing for some time. Then GYROBO turns right and makes a left turn at one point contact with floor. It is unfortunate that a 360 degrees turning task is impossible with current design of GYROBO. The reason is that control of the tilting angle of the flywheel is difficult due to the mechanical design. In order for GYROBO to make a 360 degrees turn, the flywheel has to be tilted in one direction. This configuration is not allowed with the current version due to limited space inside the inner wheel.

5.3 Straight line following control

Final experiment is for GYROBO to move the straight line inside the building. The straight line trajectory is given by an operator through wireless communication.

Initially, an operator holds GYROBO by hands to make the system stable balancing. After releasing, GYROBO tries to balance itself by tilting a little bit on the right hand side due to the slip of the wheel with the floor. Then GYROBO moves forward as commanded. Fig. 9 demonstrates tracking control of the straight line trajectory. Speed of GYROBO is about 0.25m/sec, which is considered as a slow movement.

Fig. 9 Straight line trajectory control

6 Conclusion

A single-wheel mobile robot is tested for balancing and driving control performances. Linear controllers enable GYROBO to be stabilized after several modifications of the mechanical design of GYROBO. Locating the center of mass of the system at the center to make symmetrical system is one of important factors for a successful balancing task. The second important design is to reduce rotational vibration of the high speed flywheel. After fixing mechanical problems, sensor filtering and fusing methods with other sensors are considered.

GYROBO successfully follows the specified trajectories in the plane given by a remote operator. Linear controllers for both roll and yaw angles are used and perform well although sensor signal in yaw direction is not available.

In the future, an additional sensor can be added to the current hardware for more accurate measurement. Then aggressive maneuvering control tasks such as moving backward, turning 360 degrees, climbing over an obstacle will be investigated through experimental studies.

Acknowledgements

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References

[1] "Segway." , http://www.segway.com
[2] K. Pathak, J. Franch, and S. Agrawal, "Velocity and position control of a wheeled inverted pendulum by partial feedback linearization", IEEE Trans. on Robotics, vol. 21, pp. 505--513, (2005).
[3] S. H. Jeong and T. Takayuki "Wheeled Inverted Pendulum Type Assistant Robot: Design Concept and Mobile Control", IEEE IROS, pp. 1932--1937, (2007).
[4] S. S. Kim and S. Jung, "Control experiment of a wheel-driven mobile inverted pendulum using neural network", *IEEE Trans. on Control Systems Technology*, vol. 16, no. 2, pp. 297--303, (2008).
[5] J. S. Noh, G. H. Lee, and S. Jung, "Position control of a mobile inverted pendulum system using radial basis function network", *International Journal of Control, Automation, and Systems Engineering*, vol. 8, no. 1, pp. 157--162, (2010).
[6] J. S. Noh, G. H. Lee, H. J. Choi, and S. Jung, "Robust control of a mobile inverted pendulum system using RBF neural network controller", *IEEE ROBIO*, pp. 1932--1937, (2008).
[7] C. L. Rui and N. H. McClamroch "Stabilization and Asymptotic Path Tracking of a Rolling Disk", *IEEE Conf. on Decision & Control*, pp. 4294--4299, (1995).
[8] Y. Xu and K. W. Au, "Stabilization and Path Following of a Single Wheel Robot", *IEEE/ASME Transactions on Mechatronics*, vol. 9, No. 2, pp. 407--419, (2004).
[9] G. C. Nandy and Y. S. Xu "Dynamic Model of A Gyroscopic Wheel", Proc. *IEEE Int. Conf. on Robotics and Automation*, pp. 2683--2688, (1998)
[10] Y. S. Xu and Y. S. Oh, "Control of single wheel robots", *Springer*, (2005)
[11] T. B. Lauwers, G. A. Kantor, and R. L. Hollis, "A dynamically stable Single-Wheeled Mobile Robot with Inverse Mouse-Ball Drive", IEEE Conference on Robotics and Automations, pp. 2884--2889, (2006).
[12] P. K. Kim, J. H. Park, and S. Jung, "Experimental Studies of Balancing Control for a Disc-Typed Mobile Robot Using a Neural Controller: GYROBO", *ISIC2010, Multi-Conference on Systems and Control*, pp. 1499--1503, (2010).