Technical Paper:

Gyroscopic Stabilization of a Self-Balancing Robot Bicycle

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This paper reports the design and development of a self-balancing bicycle using off-the-shelf electronics. A self-balancing bicycle is an unstable nonlinear system similar to an inverted pendulum. Experimental results show the robustness and efficiency of the proportional plus derivative controller balancing the bicycle. The system uses a control moment gyroscope as an actuator for balancing.

Keywords: bicycle, Control Moment Gyro (CMG), real-time, control and FPGA

1. Introduction

The bicycle's environmental friendliness and light weight make it a good means of. A robot bicycle is, by nature, an unstable system whose inherent nonlinearity makes it difficult to control. This in turn, brings interesting challenges to the control engineering community. Researchers have been exploring different mechatronic solutions for dynamically balancing and maneuvering robots bicycles.

A self-balancing robot bicycle uses sensors to detect the roll angle of the bicycle and actuators to bring into balance as needed, similar to an inverted pendulum. It is thus an unstable nonlinear system.

A self-balancing robot bicycle can be implemented in several ways. In this report, we introduce these methods, and focus on one of the mechanisms involving a Control Moment Gyro (CMG), – an attitude control device typically used in spacecraft attitude control systems. A CMG consists of a spinning rotor and one or more motorized gimbals that tilt the rotor's angular momentum. As the rotor tilts, changing angular momentum causes gyroscopic precession torque that balances the bicycle.

2. Background

A bicycle is inherently unstable and without apporpriate control, it is uncontrollable and cannot be balanced. There are several different methods for balancing of robot bicycles, such as the use of gyroscopic stabilization by Beznos et al. in 1998 [1], Gallaspy in 1999 [2], moving of the Centre Of Gravity (COG) or mass balancing by Lee and Ham in 2002 [3], and steering control by Tanaka and Murakami in 2004 [4]. A very well-known self-balancing robot bicycle, Murata Boy, was developed by Murata in 2005 [5]. Murata Boy (**Fig. 1**) uses a reaction wheel inside the robot as a torque generator, as an actuator to balance the bicycle. The reaction wheel consists of a spinning rotor, whose spin rate is nominally zero. Its spin axis is fixed to the bicycle, and its speed is increased or decreased to generate reaction torque around the spin axis. Reaction wheels are the simplest and least expensive of all momentum-exchange actuators. Its advantages are low cost, simplicity, and the absence of ground reaction. Its disadvantages are that it consumes more energy and cannot produce large amounts of torque.

Fig. 1. Murata Boy [5], self-balancing bicycle riding robot.

In another approach proposed by Gallaspy [2], the bicycle can be balanced by controlling the torque exerted on the steering handlebar. Based on the amount of roll, a controller controls the amount of torque applied to the handlebar to balance the bicycle. Advantages of such a system include low mass and low energy consumption. Disadvantages include the ground reaction force it requires and its lack of robustness against large roll disturbance.

Among these methods, the CMG, a gyroscopic stabi-

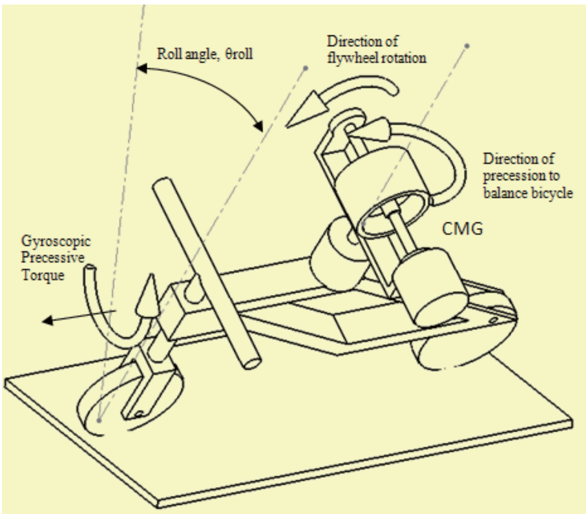


Fig. 2. Balancing of bicycle using gyroscopic precession torque generated by CMG.

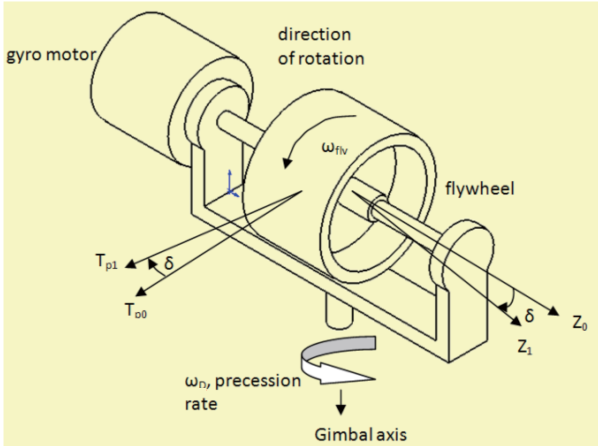
lizer is a good choice because its response time is short and the system is stable when the bicycle is stationary. The CMG consists of a spinning rotor with large, constant angular momentum, whose angular momentum vector direction can be changed for a bicycle by rotating the spinning rotor. The spinning rotor, which is on a gimbal, applies torque to the gimbal to produce precessional, gyroscopic reaction torque orthogonal to both the rotor spin and gimbal axes. A CMG amplifies torque because small gimbal torque input produces large control torque to the bicycle. The robot described in this paper uses the CMG as a momentum exchange actuator to balance the bicycle. Advantages of such a system include its being able to produce large amounts of torque and having no ground reaction force. Disadvantages include its greater energy consumption and its greater weight.

3. Dynamic Model of CMG-Controlled Bicycle

The bicycle relies on gyroscopic precession torque to stabilize the bicycle while it is upright. **Fig. 2** shows how precession torque balances the bicycle.

When the bicycle is tilted at angle θ_{roll} as shown in **Fig. 2**, an Inertia Measurement Unit (IMU) sensor detects the roll angle. Roll data is fed to an onboard controller that in turn commands the CMG's gimbal motor to rotate so that gyroscopic precession torque is produced to balance the bicycle upright. The system uses a single gimbal CMG and generated only one axis torque. The direction of output torque change is based on gimbal motion. **Fig. 3** shows the components and vectors of a single gimbal CMG. The system uses gyroscopic torque to balance the bicycle.

The flywheel angular nominal speed is 4480 rpm so ω_{fly} is 469 rad/s.



Definition
ω_{fly} is flywheel angular velocity
Z_0 is flywheel angular momentum vector at time t
Z_1 is flywheel angular momentum vector at time (t + dt)
δ is precession angular displacement
Tp_0 is the precessive output torque at time t
Tp_1 is the precessive output torque at time (t + dt)

Material of flywheel	Brass
Mass	2.02kg
Polar moment of inertia, J	8.83E-3 kgm^2
Radius of gyration, k	0.066m
Diameter	0.153m
Power	12 W

Fig. 3. Components of a single-axis CMG.

Angular momentum of rotor,

$$\begin{aligned} Z &= J\omega_{\text{fly}} \\ &= 0.00883 \times 469 \\ &= 4.14\ \text{kg} - \text{m}^2/\text{s} \end{aligned}$$

If a rotational precession rate of ω_{D}, is applied to the spinning flywheel around the gimbal axis, precession output torque, T, which is perpendicular to the direction of ω_{fly}, and ω_{D} are generated as shown in **Fig. 3**. The gimbal motor has an angular velocity of 5 rad/s, so the gimbal precession output torque generated is:

$$\begin{aligned} T_{\text{p}} &= J\omega_{\text{D}} \\ &= 4.14 \times 5 \\ &= 20.7\ \text{Nm} \end{aligned}$$

The dynamic model of a bicycle is based on the equilibrium of gravity and centrifugal force. A simplified model for balancing is derived using the Lagrange method and neglecting force generated by the bicycle moving forward and steering. This model is based on the work of Parnichkun [6], which is a simplified dynamics model of the bicycle for balancing control while derived using the Lagrange method and neglecting force generated, as stated, by the bicycle moving forward and steering. With reference to **Fig. 4**, the system, consisting of two rigid body links, has as its first link a bicycle frame having 1 Degree-Of-Freedom (DOF) rotation around the Z axis. The sec-