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Self-Balancing Bicycle using Reaction Wheel

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Abstract:
This paper reports to design and build a bicycle that is capable of balancing with or without a rider. The Autonomous bicycle will employ a control system to keep itself from falling over while stationary or in motion, and be propelled by a motor. Based on inverted pendulum concept, the goal of this project is to build a bicycle prototype capable of balancing itself using a reaction wheel. In order to maintain the balance, the robot reads IMU sensor input and calculate the tilt angle and reacts accordingly to maintain a vertical position. Sensor data is first processed to generate a noiseless data of the bicycle state and then fed into a control system which outputs a balancing torque to motor incorporated with the reaction wheel. The requirements include that the bicycle should be capable of balancing vertically without falling over.

Keywords: Self balancing bicycle, Reaction wheel, Inverted pendulum.

I. INTRODUCTION

Bicycles are a common form of exercise, recreation and transportation used by millions and billions of people. They can also serve to provide physical therapy. Bicycle are a low impact form of exercise that can train strength, stamina, balance and coordination. Though one may consider riding a bicycle to be a fairly simple task, but it is not that simple for many people. This includes young children, adults who have never learned or have some disabilities. Autonomous Bicycle could provide balancing assistance without affecting the experience of riding a bicycle and this could provide great benefit to these groups of individuals. Such a system could be used as a teaching tool, as well as a physically therapeutic device. This problem of balancing a bicycle is common to a well-known inverted Pendulum problem. An inverted pendulum is a pendulum which has its center of mass above its pivot .The pendulum here is similar to a bicycle system. While a normal pendulum is stable, an inverted pendulum is unstable, and must be balanced in real time to remain upright. In this case, the bicycle is a rigid body which can rotate around its contact point with the ground hence forming an inverted pendulum. A bicycle motion has multiple degrees of freedom, but this project aims to stabilize is this tilt angle around the point of contact with the ground relative to the direction of gravity which is only one of the degrees of freedom of bicycle.

II. BACKGROUND

A bicycle is unstable and without appropriate control, it is uncontrollable and cannot be balanced vertically. There are different methods of balancing 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 Hem in 1996[3], and steering control by Tanaka and Murakami in 2004[4]. A very well-known self-balancing robot bicycle, Murata Boy[5], was developed by Murata in 2005. Murata Boy uses a reaction wheel inside the robot which acts as a torque generator, as an actuator for the balancing of the bicycle. The reaction usually wheel consists of a spinning rotor, whose spin rate is nominally zero. Its spin axis is fixed to the bicycle. Its speed is increased or decreased to generate reaction torque around the spin axis according to the requirement. Reaction wheels are the simplest and least expensive of all momentum exchange actuators. Its advantages are simplicity, low cost, and the absence of ground reaction. Its disadvantages are that its more energy consuming and cannot produce large amounts of torque. In another approach proposed by Gallaspy, the bicycle can be balanced by controlling the torque applied on the steering handlebar. Based on the amount of roll i.e. tilt angle, a controller controls the amount of torque applied to the handlebar for balancing the bicycle. Advantages of such a system are low mass and low energy consumption. Disadvantages are the ground reaction force it requires and its lack of robustness against large tilt angles.

III. OBJECTIVE

Challenges over controlling the bicycle are mainly: Balancing the two-wheeler bicycle without support of any extra support is one of the biggest challenges. A bicycle remains upright when it is steered so that the ground reaction forces exactly balance all the other internal and external forces, such as gravitational if leaning, inertial or centrifugal if in a turn, gyroscopic if being steered, and aerodynamic if in a crosswind. Steering is supplied by a rider or by the bike itself under certain circumstances. One other way that a bicycle can be balanced is by applying appropriate torques between the bike and rider. This automatic balancing is generated by a combination of several effects that depend on the structure, geometry, mass distribution, and speed of the bicycle. Tires, suspension, steering damping, and frame flex also influence the balancing, especially in motorcycles.

IV. DESCRIPTION OF SYSTEM

The three designs are described below with consideration of physical complexity, power requirements, programming code complexity, cost, and closeness to resembling a bicycle. There are multiple number of motors and sensors required in this project. The reaction time and starting and stopping are also taken into special consideration. Power is also required which include the battery necessary to provide the system with continuous power supply. The battery is dependent on the weight of the model, number of motors needed for that design, and the torque demands of the motor(s) for the control system.

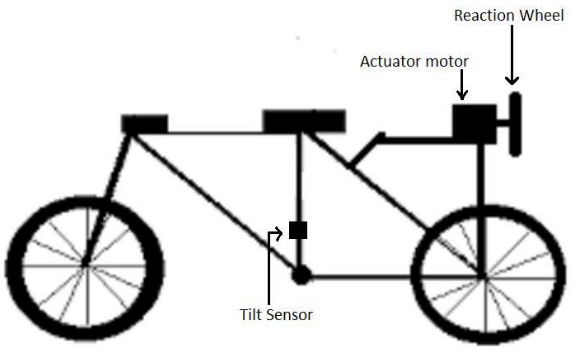

Figure.1. Mechanical model

The reaction wheel design employs a flywheel which rotates about an axis parallel to the frame of the bicycle. This design converts the bicycle as an inverted pendulum with a fixed pivot where the bicycle wheels meet the floor. As the bicycle falls to one side, a motor mounted on the bicycle exerts a torque on the flywheel, generating a reactionary torque on the bicycle, which restores the balance of the bicycle. There are several advantages of the flywheel design. This design is very stable giving the bicycle capability to balance even in a stationary position. Due to the simplicity of the design of the autonomous bicycle model, the controller would be relatively straightforward to implement. This design would also allow the bicycle to travel in a straight line with little or no deviations.

A. *Control Overview*

The control of the bicycle is simple and straightforward. This includes reading data from sensor, filtering the data, applying control algorithms on the data, and sending control signal to the actuators. All the filtering of data and generation of control signal is done by a microcontroller.

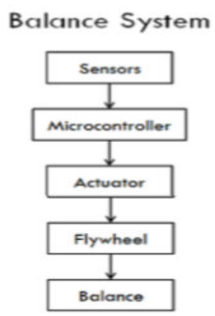

Figure. 2. Process flow diagram

The STM32F103C8T6 (the selected microcontroller) reads the output of the accelerometer and the gyroscope via the 12-bit analog-to-digital converter. This collected value is used to calculate the tilt angle of the bicycle. The measured angle is treated with a PID algorithm, and output generated is scaled to a corresponding voltage and fed to the motor controller. The motor controller then outputs a voltage to the DC motor. This motor geared down, and ultimately actuates the flywheel. The torque exerted on the flywheel, generates a reaction torque which is exerted on the bicycle.

B. *Microcontroller unit*

The microcontroller selected to control the balance of the bicycle is the STM32F103C8T6.

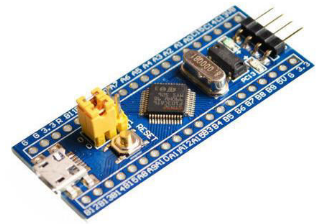

Figure.3 .STM32F103C8T6 Microcontroller

The processing unit used is STM32 32-bit Arm Cortex MCU. It has multiple I/O (Input / Output) ports at 3.3V voltage level and also 5V voltage level, onboard ADC (Analog to Digital Converter) and PWM (Pulse Width Modulation) outputs for motor control. It also has I2C port which is used to communicate with other I2C enabled devices. It can be programmed easily which make it extremely popular in robotics applications. Here it performs the following functions:

- Reading outputs of Rate Gyro and Accelerometer via I2C port.
- Processing the input signals.
- Periodic recalibration of gyro.
- Display of angle & other data.
- Control of actuator unit.

C. *Angle Sensor*

Tilt angle sensing is the main part of this project and the most difficult part as well.

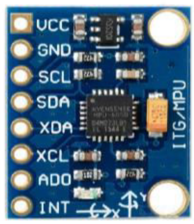

Figure.4. MPU6050 motion sensor

To measure the bicycle's angle, an accelerometer and a gyroscope is used, and their values are combined using a Kalman filter. Integrating the values of these two sensors proves useful when calculating the bicycle's tilt angle. Accelerometers is used to measure the angle with respect to gravity directly, but they are highly susceptible to noise. Gyros produce noiseless values, but they measure angular velocity. As a result, the gyro output is integrated to obtain a measurement of angular position or tilt angle. This integration gives an error known as drift, which is a drawback of the gyro. Integrating both sensors gives the output which is accurate tilt angle rather than value produced by one sensor only. This is done by the implementation of a filter, which combines the advantages and eliminates the drawbacks of each sensor. The output produced by Kalman filter after combining accelerometer and gyroscope date is smooth and noiseless.

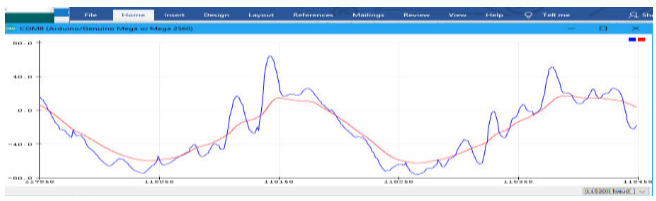

Figure.5 .Output of Kalman filter

D. *Actuator unit*

As the bicycle banks to one side, we need to apply a restoring force to return the bicycle to vertical position. A reaction wheel pendulum model is used for the balancing purpose. The components used are:

- High torque 12V DC motor
- A reaction-wheel
- Motor driver L298N

The flywheel requires a large amount of power, so a fairly powerful motor and a gear reducer are required. In order to choose the motor, the designed frame and layout of components, are considered as well as the calculations to model a simple inverted pendulum, are given as an input into a V-REP simulation.This simulation gives values in determining the power, torque and velocity that the motor required. To meet these requirements, a High torque 12V DC motor is used. A capacitor is connected across the motor which charges and discharges during the on and off time respectively, thus behaving like an integrator. The torque generated by the motor and the reaction torque generated by the reaction wheel is a function of the average value of current supplied. The tilt angle is considered and the reaction wheel is rotated proportionally to generate an equal and opposite torque to balance the bicycle. But just proportional controller overthrows the bicycle to another side which is not the required situation. To fix this we need a control algorithm which can damp this periodic motion and make it stable at the vertical mean position after some time. This is where PID (Proportional Integral and Derivative) Controller comes in action.

E. PID Controller

A proportional–integral–derivative–controller (PID controller) is a control loop feedback mechanism. It is widely used in industrial control systems and a variety of other applications.

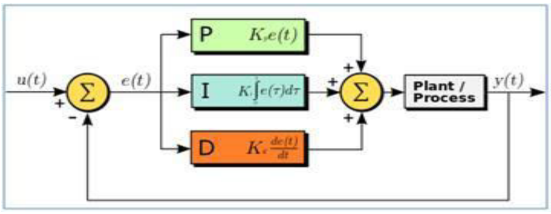

Figure.6 . PID Controller

In the Autonomous bicycle a PID controller is used to generate the control output for the reaction wheel mechanism. The tilt angle of the bicycle with respect to the vertical axis is considered as an error in the system and fed to the proportional controller of the PID system. The difference in the tilt angle of the bicycle with last measured angle or the angular velocity is fed to the Differential controller of the PID system. The error is integrated over time and then fed to the integral controller of the PID system. Along with these errors, the angular velocity of the reaction wheel is also taken as an error. This is done as we have limitation of the angular velocity of the motor after which even if the power going to the motor is increased, there will be no significant change in the torque generated, which leads to no reaction torque. To overcome this saturation condition, the angular velocity of the reaction wheel is also taken as feedback from the system and fed to the controller. With a tuned PID parameters, an output is generated by the controller and this output is considered as an input for the reaction wheel motor torque and as equivalent amount of power is provided to the motor. Taken tilt angle of the bicycle as 'θ' and angular velocity of reaction wheel as 'ω', then the output of the controller will be:

$$PID = K_{p1} * \theta + K_{d1} * d\theta/dt + K_{i1} * \int \theta \, dt + K_{d2} * \omega$$

V. CONCLUSION

This paper is concentrated on the bicycle using reaction wheel. Tilt angle information to roll axis or the axis of the bicycle is attained through the sensor integration of Kalman filter between accelerometer and gyroscope. The simplest PID controller is applied balance the bicycle about the axis. As future works, robust controller for the vertical balancing axis to minimize effects of external disturbances, such as wind, sudden collision etc. and giving driving capabilities to the bicycle with straight line trajectory and a curved trajectory with maintained tilt angle such as to balance the centrifugal force generated at the time of turning the bicycle or providing the steering are currently being worked upon. Bicycles are sustainable and practical personal mobility solutions for campus environments, or for pedestrian facilities. However, many campus environments also experience traffic congestion, parking difficulties and pollution from other vehicles. It appears that pedal power alone has not been sufficient to decrease the use of petrol and diesel vehicles, and therefore we need to investigate both the reasons behind the continual use of environmentally unfriendly transport, and discover potential solutions. This paper presents the solution by which bicycle can again become a mode of personal transport rather than using petrol or diesel vehicles.

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