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Development and control of a unicycle robot with double flywheels

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ABSTRACT

Balancing the unicycle robot is a challenging topic for control and mechanical design. The robot has to robustly balance itself in both longitudinal and lateral directions under uncertain disturbances and inherent non-linear effects. This paper presents the development and control of a unicycle robot which utilizes double-flywheel technique for roll (lateral) control and the inverted-pendulum technique for pitch (longitudinal) control. The non-linear dynamic model is derived by Lagrangian approach. The linearized model is approximated around upright position and identified. The unicycle robot prototype is designed and controlled. Linear quadratic regulator with integral action (LQR + I) is proposed to balance the robot in both directions and compared with the conventional LQR. Simulation and experimental results of balancing control and robot position control are presented. The results significantly show superior performance of LQR + I over LQR.

1. Introduction

Unicycle robot is a mobile robot with a single ground contact. It requires less space for mobility compared to bicycle robot, four-wheel/four-leg robot, etc. It can be useful in an area with very limited or narrow space. Balancing of this kind of robot has been a very challenging and interesting topic for the researchers in dynamic control because the robot is a highly non-linear and unstable system. It importantly requires the controller that robustly stabilizes the robot at the upright position and simultaneously tracks the referenced command. Several control techniques are proposed to balance the unicycle robot. Schoowinkel [1] proposed the turntable mechanism which imitates a human riding the unicycle. The lateral falling down of robot is avoided by the torque from twisting the robot body. However, it was unsuccessful because of insufficient torque generated by the mechanism. Sheng and Yamafuji [2] improved the previous technique by using an asymmetric turntable that can produce greater torque. The simulation and experimental results showed that the improved unicycle robot could be powerfully balanced.

Mass balancing is a technique based on changing a center of gravity. Nakajima et al. [3] proposed mass balancing technique for their rugby ball-shaped robot. This shape made possible of rolling balancing and steering control. Daud et al. [4] proposed another approach by swinging a pendulum sideward to balance the robot in rolling direction. The relationship between leaning angle of the robot and pendulum angle was determined and simulated.

Lee et al. [5] introduced a couple of air blowers on opposite sides of their robot in order to produce the balancing force along roll axis.

One of the most well-known technique is based on angular momentum concept. A spinning wheel, or flywheel, is attached to the robot for maintaining the angular momentum. The flywheel is accelerated or decelerated to generate the balancing torque in roll angle. Majima et al. [6,7] proposed a single-flywheel technique for balancing a unicycle robot. The flywheel is set at a fixed axis and perpendicular to the robot wheel. Also, Daoxiong et al. [8] applied the fixed axis of single flywheel for stabilizing roll angle of robot on an inclined plane. However, this technique is limited by the maximum speed and acceleration limit of the motor.

Variable axis flywheel is another technique for balancing robot. The flywheel constantly spin and maintain the angular momentum. When angular momentum is changed by rotating the flywheel axis, it thus produce the rolling torque to the robot. Xu and Au [9] applied this technique for roll-angle balancing of a mono-wheel robot (Gyrover). Their stabilization mechanism is inside the wheel. Also, Thanh and Parnichkun [10] utilized the same technique in bicycle robot, called BicyRobo. However, there exists an inherited drawback in the form of coupled rolling-heading effect.

Besides the balancing mechanisms, many control algorithms were proposed to stabilize the unicycle robot. Linear controllers; for examples PID controller and LQR were implemented in many research works [1–3,5,8,9]. Some researchers [5,11] decoupled roll and pitch controls. Robust controls were also applied to the robot, such as H_2/H_∞ control [10] and fuzzy sliding-mode control [11].

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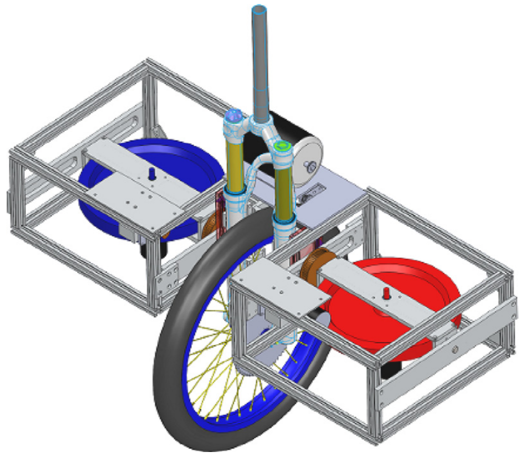

Fig. 1. Completed model of unicycle robot.

To solve the coupling of roll and yaw (heading) problem, a new mechanism design using double flywheels is proposed to decouple the roll and yaw motion. This paper presents the development and control of a unicycle robot with double flywheels. Both flywheel sets are decoupled from each other. They rotate in opposite directions at the same speed so that the vertical precession torques from both flywheels can be completely canceled when both flywheel axis are aligned. Since there are two flywheel sets, the robot can be stabilized in roll axis and the robot's heading can be controlled at the same time. As the result, the roll and heading angles of the robot can be controlled independently. Using double flywheel sets results in more torque for roll balancing than using only one flywheel set. Linear quadratic regulator with integral action (LQR + I) is proposed to balance the robot in both directions. The performance of LQR + I and the conventional LQR are evaluated and compared in this paper.

The unicycle robot with double flywheels is designed and developed in order to prove the new design concept of roll and yaw controls of a unicycle. The two flywheel sets are located at the left and the right of the robot's body in order to accommodate calibration and adjustment. However these two flywheel sets can be located as a stack in the robot's body in order to occupy less space later during the implementation phase.

2. Conceptual design

Basically, unicycle robot has only a single contact point on ground. It can possibly fall in lateral (roll) and longitudinal (pitch) directions. On balancing the robot based on variable axis single flywheel, the generated torque unintentionally affects the robot's heading. To solve the problem, our double-flywheel technique is introduced to eliminate the heading effect by rotating in opposite directions and producing more rolling torque in the robot design. Both flywheels are installed on both sides of the robot as shown in Fig. 1.

In roll stabilizing, double flywheels are to produce torque for balancing the unicycle robot. The produced torque (τ_{roll}) depends on angular momentum (L_s) and angular precession speed ($\dot{\Omega}$) as shown in Fig. 2. In pitch stabilizing, the inverted-pendulum technique is typically applied to balance the robot. In heading stabilizing, it is controlled by the vertical precession torques from both flywheels. The advantage of using double flywheels over single flywheel in the unicycle robot is that the former offers both roll and yaw controls at the same time while the later can only control either roll or yaw motion at a time.

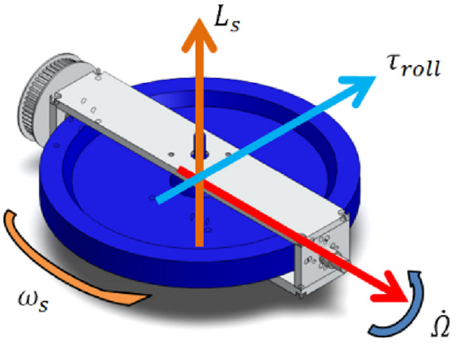

Fig. 2. Torque generated by the flywheel.

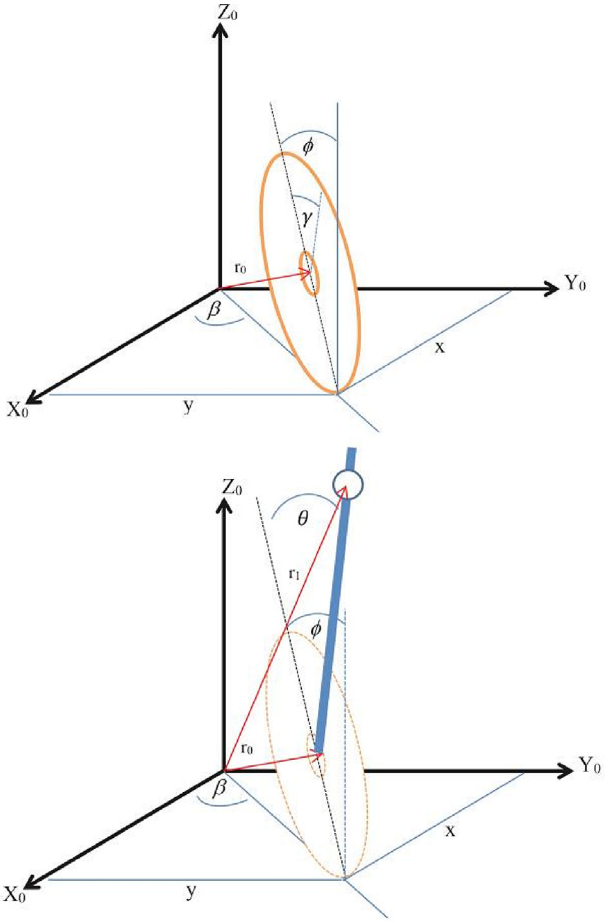

Fig. 3. Unicycle robot model: wheel of the robot (top) and body of the robot (bottom).

3. Robot dynamic model

3.1. Mechanical model

The dynamic model of unicycle robot is derived by two separated subsystems, unicycle wheel and the robot body shown in Fig. 3. Both are referred to the fixed world coordinates.

The Euler–Lagrange equation is applied for deriving the dynamic model of the unicycle robot. Friction in the system is assumed small and negligible. The dynamic equation is obtained using Eq. (1).

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right) - \frac{\partial L}{\partial q} = f \tag{1}$$