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Attitude control of an airborne two wheeled robot

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Abstract: The problem of balancing a two wheeled robotic platform has been intensively studied and well understood. However in such studies, the mathematical model of the robot is commonly derived under the assumption that the robot remains constant contact with the ground. This assumption limits the movement of the robot to continuous ground surface. In other words, any momentary airborne situation, such as traversing down a flight of stairs or falling off edges will render the control algorithm ineffective and cause the robot to fall upon landing. In this paper, the dynamics of a free falling two wheel robot are investigated and a novel attitude control scheme is proposed. We proposed using the wheel of the pendulum as a reaction wheel to provide control torque for correcting the robot's attitude in air and ensure a safe landing. The effectiveness of the proposed approach is demonstrated through both simulations and actual implementation.

Keywords: two-wheeled balancing robot, free fall, dynamic balancing, attitude control

1 INTRODUCTION

Mobile robots that are deployed into human environment will need to traverse through non-continuous terrains such as steps or stairs in order to navigate around certain area. Various kinds of robots have been designed to tackle this problem. Most notably biped type humanoid robot such as ASIMO [1] are able to traverse up and down stairs. However, due to its complexity and price of manufacturing, deployment of biped type humanoid robot is still uncommon and not economically practical. As for wheeled robots, maneuvering through non-continuous terrains remains a challenging open problem.

Various statically stable mobile wheeled robots have been developed for tackling such problem. For example the Sojourner [2] developed by NASA and the Shrimp robot [3] developed by EPFL uses a combination of adaptive legs with the efficiency of wheels to enable the robot to traverse through uneven terrain and steps. These approaches rely on the redundancy of static points of support on the base to provide stability to the robot during climbing up/down steps. Drawbacks on these robots are increased complexity in structure and control and increased size. In human environment where workspace is limited, their navigation ability may be restricted since they typically require a larger workspace.

In contrast, dynamically stable robots like JOE [4], Ballbot [5] which use active control to achieve balance possess greater flexibility in maneuvering and are more resistant to external disturbance. These robots also have a smaller footprints and possess a near-zero turn radius for moving in a limited space. Given the robustness against applied external forces, these robots prove to be more usable when deployed into human environment.

This paper explores the possibility of a two wheeled robot to traverse down a non-continuous ground step. The dynamics of the free falling motion are investigated and a novel attitude control scheme is proposed. The proposed approach extends the ability of the two wheeled robot to traverse through rough and edgy terrains. During free fall, a two wheel robot behaves similarly to a reaction wheel pendulum, with pivot point at the center of mass. Hence it is possible to use the momentum of the wheels to generate correction torque to alter the orientation of the robot and ensure a safe landing. Two separate feedback control schemes designed using the linear-quadratic controller (LQ) are employed for two phases of airborne falling and ground contact. A switching controller selects the adequate controller according to the situation. The effectiveness of the proposed approach is demonstrated through simulations and actual implementation.

2 RELATED WORK

IHop [6] developed by the Flow Control and Coordinated Robotics Labs, UCSD uses an interesting approach, similar to our proposed technique to balance a hopping robot. IHop demonstrated that it is possible to use the wheels as reaction wheels to alter the movement of the center of mass of the robot to achieve dynamic balancing. However in the case of IHop, dynamic balancing of the robot is demonstrated only on flat ground. Experiment on traversing through steps was not demonstrated. Kikuchi et al [7] proposed using vibration of a 2-DOF system as a hopping mechanism for the robot. The robot uses a moving mass and potential energy stored in springs to achieve soft landing through a vertical step. However, the robot presented is statically stable and exhibits drawbacks that were discussed earlier.

3 DYNAMIC MODEL

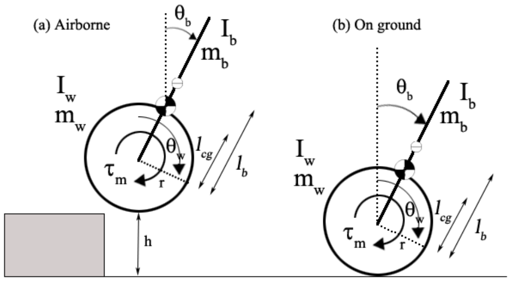

Fig. 1: The schematic of two wheeled robot

In this section, the dynamics of the robot is presented. To simplify the problem, a few assumptions are made. First, it is assumed that the orientation of the robot in roll direction remains constant during flight and hence attitude control in roll direction is negligible. Under this assumption, the problem can be simplified into a two dimensional pendulum problem. Second, the moment of inertia of the wheels is sufficiently large in order to be able to act as a reaction wheel to alter the momentum of the robot. This assumption ensures that the system is controllable without introducing additional actuating mechanism. Mathematical models of the robot during ground contact and airborne phases are derived according to the schematic shown in Fig.1 corresponded to the parameters in Table 1. On ground, the robot behaves just like an ordinary two wheeled pendulum robot whereas during airborne phase, the robot behaves like a reaction wheel pendulum with the pivot point on the center of mass of the robot. Due to large available literatures on derivation of the dynamic models of two wheeled pendulum and reaction wheel pendulum [8][9][10], detailed step-by-step derivation of the mathematical model is omitted.

Table 1: List of symbols

m_b	Mass of body
m_w	Mass of wheels
I_b	Inertia of body around center of mass
I_w	Inertia of wheels around center of mass
r	Wheel radius
l_b	Length of wheel axis to body's center of mass
l_{cg}	Length of wheel axis to robot's center of mass
g	Gravity
θ_b	Tilt angle of robot body
θ_w	Rotational angle of wheels
τ_m	Motor Torque

3.1 On ground

Using Lagrangian mechanics the equation of motion of the robot traveling on ground can be easily obtained [10]. The equations of motions are then linearized and put into the form of state-space representation for controller design as described in the next section,

$$\dot{x}_g = F(x,u) = A_g x_g + B_g u \tag{1}$$

where $x_g = \begin{bmatrix} x_{g1} & x_{g2} & x_{g3} & x_{g4} \end{bmatrix}^{\mathrm{T}}$ is the state vector and u is the scalar motor torque input. By choosing $x_{g1} = \theta_w$, $x_{g2} = \dot{\theta}_w$, $x_{g3} = \theta_b$, $x_{g4} = \dot{\theta}_b$, and $u = \tau_m$, we obtain

$$A_g = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & a_{g23} & 0 \\ 0 & 0 & 0 & a_{g34} \\ 0 & 0 & a_{g43} & 0 \end{bmatrix}, \quad B_g = \begin{bmatrix} 0 \\ b_{g2} \\ 0 \\ b_{g4} \end{bmatrix} \tag{2}$$

The values of a_{g23}, a_{g34}, a_{g43}, b_{g2} and b_{g4} are specific to actual robot configuration [10].

3.2 Airborne

Similarly, using Lagrangian mechanics, the equations of motions of the robot during airborne can be derived, linearized and put into state space form as shown below,

$$A_a = \begin{bmatrix} 0 & 1 & 0 \\ a_{a21} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad B_a = \begin{bmatrix} 0 \\ b_{a2} \\ b_{a3} \end{bmatrix} \tag{3}$$

Here, only three of four available states are used to describe the motion of the robot, namely θ_b, $\dot{\theta}_b$ and $\dot{\theta}_w$. The rotational angle of the wheel are not controlled during airborne phase and hence not included into the motion model. Note that in the case of airborne, unlike conventional reaction wheel pendulum where the pivot lies on the base of the pendulum, the pivot point actually lies on the center of mass of the robot.

4 CONTROL

The control of the robot is divided into two phases. When the robot is moving on the ground, a linear quadratic(LQ) controller designed around equation (2) is employed. The feedback control torque τ_m is given by

$$\tau_{gm} = -K_g x_g + k_{g1}\theta_{wref} \tag{4}$$

where $K_g = \begin{bmatrix} k_{g1} & k_{g2} & k_{g3} & k_{g4} \end{bmatrix}$ is the feedback gain obtained from the LQ controller and θ_{wref} is the reference value for controlling the rotational angle of the wheel and hence the horizontal position of the robot.

When the robot falls off a step, a different LQ controller designed based on equation (3) is employed to control the attitude of the robot. The feedback control torque in this case can be written as

$$\tau_{am} = k_{a1}(\theta_{bref} - \theta_b) - k_{a2}\dot{\theta}_b - k_{a3}\dot{\theta}_w \tag{5}$$

where k_{a1}, k_{a2} and k_{a3} are feedback gains computed from LQ controller. θ_{bref} is the reference body tilt angle during airborne.

Additionally, a simple switching controller is used to select appropriate controller depending on the height of the robot above ground.

$$\tau_m = \begin{cases} \tau_{gm} & \text{for} \quad |h| \leqq h_{threshold} \\ \tau_{am} & \text{for} \quad |h| > h_{threshold} \end{cases} \tag{6}$$

where h is the height of the robot above ground and $h_{threshold}$ is the height threshold value determined experimentally.

5 SIMULATION RESULTS

Before building an actual experimental platform, computer simulation is carried out to test the viability of the proposed idea. Based on our assumptions made in section 3, our problem is simplified into a 2 dimensional problem and hence in simulating the problem, a 2 dimensional simulator, Box2D [11] physics engine is used. The simulation results show that the robot is able to land and remain upright from a fall height of 0.25 meters. By actively controlling the rotation of the wheel, it is possible to generate sufficient torque to alter the angle of tilt of the robot body to ensure safe landing. However in this simulation, issues on motor torque limit versus motor size were not taken into consideration and hence simulation results might be biased.

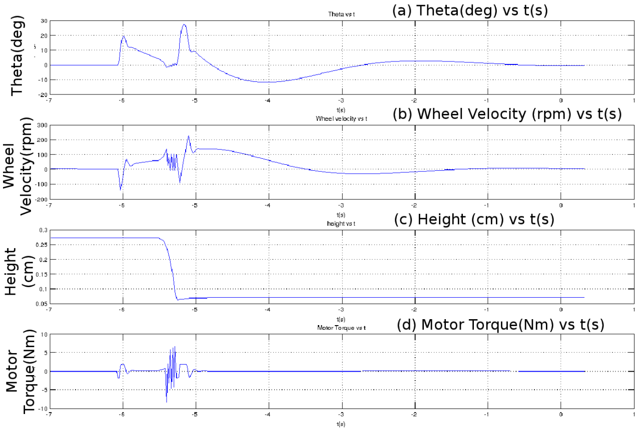

Fig. 2: Simulation results: freefall using attitude control

6 EXPERIMENTAL PLATFORM

In addition to simulation results, an experimental two wheeled mobile robot platform (Fig.3) is constructed to evaluate the validity of the controllers. The robot is equipped with an inertia measurement unit (IMU) consists of a 3-axis accelerometer and a 2-axis gyroscope and a DC motor with encoder. Kalman filter is used to estimate the angle of tilt and angular velocity of the body. As for calculating the angular velocity of the wheel, instead of direct differentiating the measurements of encoder to obtain the angular velocity, an alpha-beta filter is used for estimation. This is due to the fact that direct differentiation of encoder measurements will introduce additional noises from non-linearities such as gear backlash. The alpha-beta filter is a simplified kalman filter with constant update gains. Values of α and β are experimentally chosen. An ultrasonic distance sensor is fitted onto the bottom of the robot to measure the height of the robot above ground. All the sensor information is measured and processed using a 32-bit ARM microcontroller running at a clock speed of 96MHz.

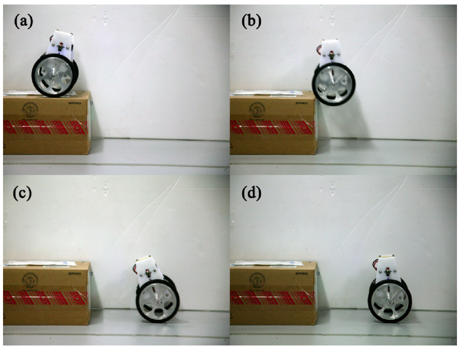

Fig. 3: Free fall of a 2 wheeled pendulum robot

7 EXPERIMENT AND DISCUSSIONS

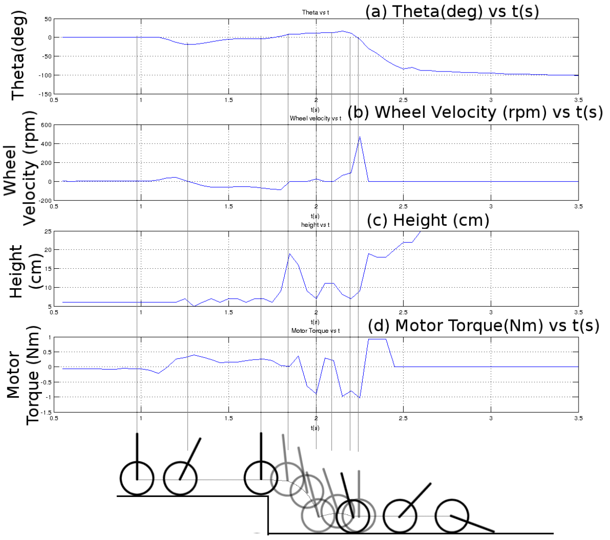

Fig. 4: Free fall using conventional feedback control

In our experiment, the robot is commanded to fall from a 20cm step (roughly same height as the robot). Figure 4 shows the experiment results of the free fall dynamics of the 2 wheel pendulum robot using conventional feedback controller. During free fall, the robot lost contact with the ground and is unable to generate balancing torque. This triggers the feedback controller to increase the feedback signal and spins the wheel faster. On landing with fast spinning wheels, large torque is applied on the robot and causes it to loose balance and fall. We have also experiment with turning off the motor

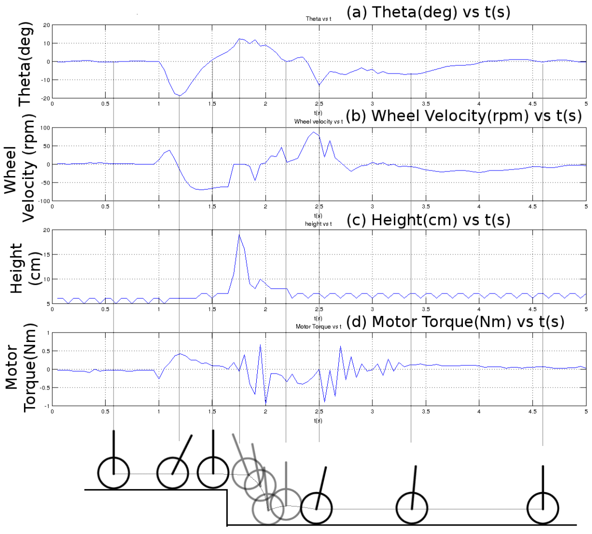

Fig. 5: Free fall with attitude control

during airborne. However, forward momentum from the fall is too large and the robot failed to recover. Figure 5 shows the experiment results of our proposed method. During the fall, the robot tilts backward in order to cope with the forward momentum during landing. Tilting control is achieved by spinning the wheels. Upon landing forward momentum neutralizes the tilt and brings the robot straight up. On-ground feedback controller take over and ensures the robot remains balance. The process of safe landing from a fall is illustrated in Fig.5.

8 CONCLUSION

In this paper we presented a unique solution enabling 2 wheeled pendulum robots to traverse down a non-continuous ground. During free fall, the 2 wheeled pendulum robot acts like a reaction wheel pendulum with pivot point at the center of mass. Hence, by actively controlling the spin of the wheels, it is possible to generate attitude controlling torque to ensure a safe landing. On ground and airborne dynamic models are presented along with two feedback controllers designed accordingly. The idea is simulated before an actual experimental platform is built. The experiment results show that the proposed method is viable and extends the maneuvering ability of 2 wheeled robots. Currently the airborne tilt angle are chosen experimentally. Future work will aim to automate airborne tilt angle control, as well as safe landing from increased height.

9 ACKNOWLEDGEMENT

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REFERENCES

[1] http://world.honda.com/ASIMO/

[2] Volpe, R., Balaram J., Ohm T., Ivlev T. (1996) The Rocky 7 Mars Rover Prototype. IEEE/RSJ International Conference on Intelligent Robots and Systems, November 4-8 1996, Osaka Japan

[3] Estier T., Crausaz Y., Merminod B., Lauria M., Piguet R., Siegwart R. (1994) An innovative Space Rover with Extended Climbing Alilities, Proceedings of Space and Robotics 2000, Albuquerque, USA, February 27-March 2, 2000.

[4] F. Grasser, A. D' Arrigo, S. Colombi, and A. Rufer, "JOE: a mobile,inverted pendulum," IEEE Transactions on industrial electronics, vol. 49, no. 1, pp. 107-114, 2002.

[5] T. Lauwers, G. Kantor, and R. Hollis, A dynamically stable single-wheeled mobile robot with inverse mouse-ball drive, in Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE InternationalConference on, 2006, pp. 2884-2889.

[6] Schmidt-Wetekam, C., Zhang, D., Hughes, R., Bewley, T., "Design, optimization, and control of a new class of reconfigurable hopping rovers," Decision and Control, 2007 46th IEEE Conference on , vol., no., pp.5150-5155, 12-14 Dec. 2007

[7] K. Kikuchi, K. Sakaguchi, T. Sudo, N. Bushida, Y. Chiba, and Y. Asai, A study on wheel-based stair-climbing robot with hopping mechanism, Mechanical Systems and Signal Processing(MSSP), ELSEVIER, Vol.22, Issue 6, 1316-1326, (2008-8)

[8] K.J Astrom, D.J. Block, M.W. Spong, The Reaction Wheel Pendulum, Morgan and Claypool, 2007.

[9] M.W. Spong, P. Corke, R. Lozano, "Nonlinear Control of the Inertia Wheel Pendulum," Automatica, vol. 37, pp.1845-1851, 2001.

[10] Teeyapan, K., Jiuguang Wang, Kunz, T., Stilman, M., "Robot limbo: Optimized planning and control for dynamically stable robots under vertical obstacles," Robotics and Automation (ICRA), 2010 IEEE International Conference on , vol., no., pp.4519-4524, 3-7 May 2010

[11] http://box2d.org/