A Two-Wheel Self-Balance Robot Capable of Jumping

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***Abstract*—Jumping is an effective way of locomotion employed by many creatures, such as locust and frog. A robot with jump ability is capable of traversing many tough terrains that wheeled, tracked, and legged robots cannot [1]. Our project purposes a prototype of rescue robot that can move inside collapsed buildings and traverse tough obstacles by hopping across them. The robot is balanced and move on two wheels, maintaining a cylindrical shape to reduce the size and avoid the potential risk of breaking support structure when landing. This report describes the idea and design of this robot. A prototype is built and tested in this preliminary stage of research.**

I. Introduction

In the past decade, with the development of electronic fabrication and control algorithm, robots have become more and more powerful and compact. Among the designs of robots, one of the most researched functions is mobility. We have seen robots showing impressive mobility in imitation to human and animal. Spot developed by Boston Dynamics is a four-leg robotic dog that could walk, run, jump, and quickly balance itself after being kicked [2]. Digit, developed by Agility Robotics, is a fully commercial humanoid robot that could walk around obstacles and do logistics works [3]. These legged robots are well-developed in their mobility, while they take a size of a human and are too expensive to expendable jobs. In some circumstances, such as reconnaissance and rescue in disaster ruins, robots are required to enter the dangerous buildings and scout the environment. In this situation, the ability of locomotion with a compact size is emphasized. The purpose of this research is to design a prototype of a robot that is able to move and balance on two wheels while jump across obstacles.

Among the various locomotion methods, jumping appears to be more effective to traverse rough terrain than traditional wheeled, tracked, and legged designs. Jumping is also a naturally selected locomotion employed by many animals and insects such as locust and frog. So far, many researches explored the jumping mechanism. The jumper developed by Kovac et al. [4] weights only 7g. It mimics the leg structure of locust and can jump obstacles more than 27 times its own size. Salto, named and developed by Haldane et al. [5], [6], has the ability to jump rapidly and repeatedly at a height of 1m by specialized leg mechanism and multi-elastic power modulation. In addition to its continuous jumping ability, Salto can actively adjust the landing point of its feet and even perform wall jumps using aerodynamic control. Recent research conducted by Professor Hawkes [7] in UCSB purposed an engineered jumper that outperformed previous biological jumper designs and jump over 30 meters high via work multiplication. Although these robots emphasize high jumping ability, they are flawed in functionality such as carrying loads and execute precise locomotion in restricted environment. These flaws make them less capable in performing useful tasks in the field.

Although jumping robot appears to be less reliable in locomotion, it could be improved by combing the jump function with conventional wheeled robots. Scout robot developed by Stoeter et al. [8] is a cylindrical two-wheeled robot. It could move through smooth surface with wheels, and when it encounters obstacles such as stairs, the external steel foot is bent by a winch and cable, storing energy for subsequent jump. In a rescue robot design, Watari et al. [1] combined a three-wheel robot with a pneumatic cylinder in order to produce instant force for the robot to traverse obstacles. Misu et al. [9] designed a compact two-wheel robot that could jump while maintaining a traveling speed of about 1.2 m/s. SandFlea, developed by Boston Dynamics [10], is a four-wheel robot equipped with a powerful combustion piston that can jump up to a building's roof. These robots largely varied in their jumping mechanism design, but shared a same purpose of allowing a wheeled robot to perform jumping as an extension of locomotion.

These designs [1], [8]-[10] successfully integrated wheeled motion and jump ability together in a compact robot design, but their multiple wheel or support foot design could be a drawback. The robot may take up extra space due to the support structure and harder to regain the upright position when it falls upside-down. Also, among the listed designs, only the robot by Misu et al. [9] is able to jump while moving. All the other designs required the robots to stop, store energy, and release it to jump, which is considered as less efficient in movement.

In this report, we purpose a solution to the issues above by removing the support structure and make the robot balance on two wheels. The two-wheel self-balancing robot has been well developed over these years. Many researches [11]-[14] have been conducted in the design and control algorithm of the self-balancing robots. An excellent example is hoverboard. Being a prominent application of two-wheel balancing system, hoverboard is already a mature commercial product in the market. Robot being able to balance and move on two wheels could restore upright position from most situations. It also could store energy while its moving since the jump mechanism is not a part of support structure.

In our research, the purposed robot has two-wheel driving system without needing extra support structure, and it is able to regain upright position from any circumstance. For the balance mechanism, we employed a PID controller to control the wheels. For the jump mechanism design, the instantaneous force is provided by compressing and releasing of a coil spring via a rack and pinon mechanism. The purpose of this prototype is to explore the possibility of employing a compact jumping mechanism on a two-wheel balance robot, aiming to improve its locomotion ability. This report is organized as follows: Section 2 describes the modeling and structure of balancing robot design; Section 3 introduces the modeling and structure of jumping mechanism; and, in Section 4, we report the result of our prototype and purpose some possible plans for the future improvement.

II. Balance Design

The structure of the two-wheel self-balance robot could be separated into four parts: microcontroller boards, sensor, motor, and power supply. The following sections will first give an overview of the overall design of the robot, then separately detail the selection of hardware for each part of the balance system design.

A. Structure Design Overview

The overall design of the robot is as shown in 1 and 2. The robot is generally separated into three parts: body, wheels, and jump mechanism. We are using 90 mm diameter wheels, so the robot is in a cylindrical shape with 90 mm diameter. The body has a length of 200 mm, and its width is restricted within the radius of wheels. This design aims to lower the center of mass and keep a cylindrical shape. A lower center of mass would require less torque from the wheel when balancing, and cylindrical shape enables the robot to rotate its body when adjusting its tilt angle. Inside the body, there are two DC motors for wheel driving, a control board for delivering PWM signals to the DC motors, a servo motor for jump mechanism, and an MPU-6050 sensor to measure acceleration and tilt angle.

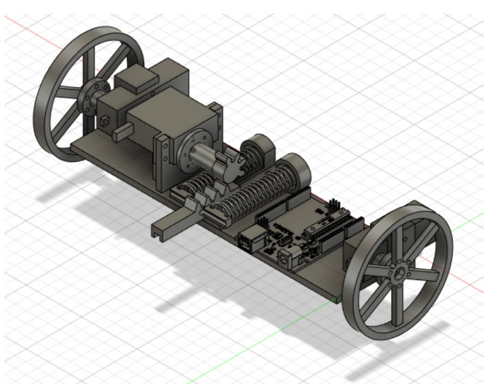

Fig. 1. 3D model of the designed robot

The jump mechanism is positioned at the center of the robot. A compression coil spring is used to store energy delivered from the servo motor. When the spring is released, a rigid rod is driven to impact with ground, making the robot to bounce up. The detailed description of jumping mechanism will be described in Section IV.

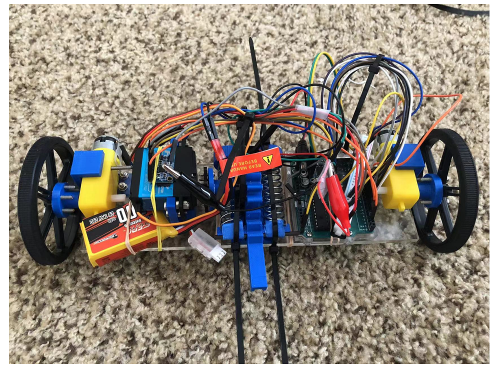

Fig. 2. Photo of the robot prototype

B. Microcontroller Board

In an automated robot design, the microcontroller board handles the feedback signals from the sensors and sends PWM signals to control the motors. In the selection of Arduino Uno Rev3 as microcontroller board for our robot, we mainly valued three features: performance, I/O pins, and the accessibility of programming resources.

For its performance, Arduino Uno is based on ATmega328P microcontroller, which features 32 KB of flash memory and 16 MHz clock speed [15], which is able to perform regular tasks, including data sampling, control computation, and signal output in a sufficiently fast manner.

The usage of I/O pins is also an important feature to consider. As described in the overall design, it has been determined that at least 2 analog input pins and 9 digital pins must be used. Arduino Uno features 6 analog input pins and 14 digital I/O pins, of which 6 provide PWM output [15]. The I/O pins on Arduino Uno board is sufficient for our prototype, and it also has more available pins for augmented functions in further iterations.

Last but not least, when programming our robot, we prefer a user-friendly programming environment with useful function libraries and reference codes. Arduino is an open-source platform where many developed libraries and open-source projects are shared. The Arduino Software IDE is based on C-language, which is compatible with most of the sensors and control boards in the market.

C. Sensor

Our design uses MPU-6050 three-axis gyroscope accelerometer developed by InvenSense [16]. Being the first integrated six-axis sensor, MPU-6050 combined a 3-axis gyroscope and a 3-axis accelerometer on the same silicon die. It has great advantage comparing to the other sensors for its low cost, low power consumption, and high-performance features. In our design, MPU-6050 is employed to measure angular velocity and acceleration of the robot body. The data is then processed by Arduino Uno and becomes control signal to balance the robot.

D. Motor and Motor Control Board

Two types of motors are implemented in the robot design: two DC motors are used to drive the wheels, and a servo motor for delivering energy to the jump mechanism. The servo motor used for jump mechanism will be detailed in Section IV. In selecting motors for wheels, we emphasized torque instead of velocity. That is because the motors need to provide enough instant torque in order to correct the pose of robot's body. We chose two DC motors, each with a gear box to increase the torque. These are common motors with rated speed of 100 RPM. The torque provided by them is tested to be enough. We chose them mainly because of their low cost and simple wiring.

For the motor control board, we used a TB6612FNG driver. It is a H-bridge driver commonly used for DC motors. It can separately control up to 2 DC motors, supporting a maximum motor supply voltage of 15V. By interfacing with Arduino Uno, TB6612FNG controls the motor speed via a PWM input signal. We chose the board because it only takes up a quarter of space comparing with L298N, another commonly used driver board, while maintaining the same functions.

E. Power Supply

For power supply, the DC motors need a voltage between 3V to 6V, the servo motor needs 4V to 8.4V, and the Arduino Uno requires an input voltage of 7-12V. In order to decrease the weight of the robot, we are only using a 7.4V 900mAh Lipo battery as the power supply in our design. The Lipo battery is one of the types of batteries that has the highest energy density. The 900mAh battery only weights 46g, which is the lowest in all the available options that could provide the voltage we need. If needed, it could also be replaced with a Lipo battery with same voltage and higher capacity.

III. Jump Structure Design

In this section, we describe the design of the jump structure of the robot. The design is separated into two parts: mechanism and our selection of motor and springs.

A. Mechanism

Our jump mechanism design employed a simple compress spring structure. As shown in 1, the jump mechanism is placed at the center of the body, where two compress coil springs are settled in slots on the base. When storing energy for jumping, the springs are compressed by a rack-and-pinion structure. The pinion converts the rotational motion of motor to the transverse motion of the rack, while the branches on the rack push and compress the springs. As the springs are fully compressed, they will be released and push the rack outward. When the rack thrusts the ground, the reaction force could launch the robot upward.

To release the rack instantly, we referred to the mechanism designed by Basement Creations [17]. It employs a partial-teeth pinion, that is a gear only has part of its teeth. The number of teeth on the pinion matches the number on the rack. When the pinion rotates, it actuates the rack by each of the matching tooth. When teeth are used up, the rack is no longer actuated and would slide out from the opening as we desired.

In our prototype, both the rack and pinion are made of 3D printed ABS material. To increase the strength of the teeth, we used dense infill in printing and each part have a 1 cm thickness. The 3D printed parts are proved to be consistent in our experiment. In the later version of the prototype, we also used a fiber carbonate rod to reinforce the branches on the rack since they are taking the greatest stress from the springs.

B. Motor and Spring Selection

In order to specify the springs that we are going to use for the jump mechanism, we first calculated the desired performance of the system and compared with the available models on the market. The total weight of the robot is estimated to be 0.5 kg, and we require the robot to jump up to a height of 0.5 m. The kinetic energy required for this jump is 2.45 J. Considering the energy loss in mechanical deficiency, the springs should certainly provide more energy when released. In our prototype, we chose the springs with spring constant 1622 N/m, with a maximum compress length of 0.041 m. The potential energy of one fully compressed spring is 1.36 J. Using two of the springs could provide 2.73 J of energy, which is sufficient for our desired performance.

The choice of motor for driving the pinion is then specified by the springs. The force required to fully compress the springs is calculated to be 133 N. The pinion is designed to have a pitch diameter of 22 mm. Therefore, the required torque delivered from the motor is required to be greater than 1.46 Nm. In our prototype, we used FT6335M servo motor to drive the pinion. It has a rated torque of 3.5 Nm. While provide enough torque, it could also be controlled directly through PWM signal from the Arduino Uno microcontroller, making the control of jump mechanism easier. In our design of jump control, the pinion should first rotate 135 degrees and hold the position, which is just enough to use up the pinion teeth and fully compress the springs. When the robot is going to jump, the motor rotates the pinion for another 45 degrees, and that make the rack to be released. The released rack is held at a position that when the pinion rotates back, the first tooth on the pinion would match the first pinion on the rack, so that the process could be repeated.

IV. Result and Discussion

In this section, we describe the test we made on this prototype of our robot. Two major experiments are made in order to test the balance and jump mechanism of the robot. From the experiments, we found the robot did not operate as we expected. A few possible solutions are described in this section.

A. Balance Ability Test

In the first test, we examined the ability of the robot in static balance. The result of static balance is as shown in 3. In the first runs, we observed that the robot kept moving forward when we asked it to perform static balance. We suspect the issue could because the center of mass deviated from the center line too much. After readjust the center of mass of the components, the robot is able to maintain a balanced state. However, it is unable to deal with some large disturbance. As long as we pushed, it would start moving in that direction and would not return. This could be an issue in the tuning of our PID controller code. To improve this issue, we purposed (1) further tuning the PID controller; (2) use a wheel motor with larger torque; and (3) redesign the structure to make the center of mass of the body in a balanced state.

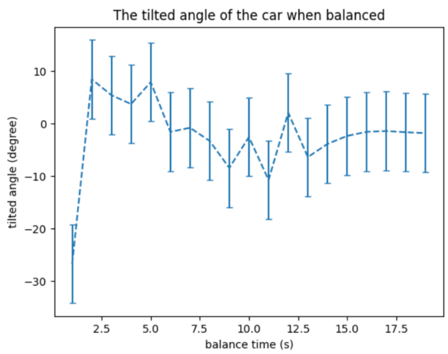

Fig. 3. Balance performance test result

B. Jump Mechanism Test

In our test of jump mechanism, we tried to drive the rack and pinion through servo motor. Then we soon realized a flaw in the mechanical design of the structure. Although the pinon is mounted on the rotator of the servo motor with screws, it is only supported on the one side. Without being properly supported, the pinion is easily deviated from its position by the force exerted on it. We had to stop the motor in order to prevent it from breaking. For this reason, any other experiments on the jump mechanism are suspended. In order to fix the issue, we need to redesign the pinion structure by adding support structure on both sides, and the mechanical strength of the connections should also be reconsidered.

V. Conclusion and Future Work

In this research, we purposed a two-wheeled self-balance jump robot. It is ideated from the concept that is to improve the locomotion ability of wheeled robots while maintaining a compact size. An initial prototype is made in order to test our nascent ideas on this robot design. In our tests, we successfully achieved static balance of the robot on two-wheels.

Our future works including further tuning the control algorithm of the balance controller to achieve more stable balance and other wheeled motion of the robot. We also need to redesign and test the jump mechanism, given our first test was unsuccessful. Further, the robot would be equipped with remote control function. This would require a WIFI or Bluetooth transmission board and a human-machine interface, such as a specialized controller or a mobile phone application. We also want it to be able to record and transmit video to the operator, and a camera module is necessary for this function.

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