Wheely: An Accessible Platform for Experimenting with Wheeled-Legged Quadrupedal Robots

William Zhang
Grade 10
Weston High School
Boston, United States of America
25zhangw@weston.org

Ke Wang
Robot Intelligence Lab
Imperial College London
London, United Kingdom
k.wang17@imperial.ac.uk

Abstract*—Wheely is a small and inexpensive wheeled-legged quadruped robot made to be an accessible method of experimenting with wheeled-legged robots. The current robotics environment lacks economic wheeled-legged quadrupedal robots for low stakes experimentation and use. The robot uses low-cost and easy to acquire servo motors for a simple, but reliable build. With total costs within $600 dollars, Wheely is around 0.2 m tall and weighs roughly 3 kg. Wheely's simplistic and small-scale nature allows it to be deployed by a single operator and is modification friendly. Wheely is the combination of the best of two worlds, wheeled and legged locomotion, allowing efficient travel on both smooth and rugged terrain. Experiments on robot were conducted in a simulated environment using Pybullet. Wheely is capable of autonomously surmounting stairs 0.05 m tall, 25% of its normal body height, using open loop gaits generated using Bezier curves. On flat surfaces, Wheely can reach speeds of up to 0.09 m/s using wheeled and 0.04 m/s using legged locomotion. Wheely's relatively low-cost and accessible nature will allow for the proliferation of wheeled-legged quadruped technologies and freedom of experimentation.

Keywords—Wheeled Robot, Legged Robot, Wheeled-Legged Robot

I. Introduction

The discovery of the wheel was one of the most important innovations in human history. Wheels let us move faster and more efficiently on smooth surfaces compared to legs. However, legged locomotion is more adaptable and allows us to navigate rugged terrain more easily compared to wheeled movement. Therefore, combining both tactics into one system would be optimal for travel on both flat and uneven terrain. However, current quadrupedal wheeled-legged robots are all extremely expensive. Wheeled-legged robots lack the more accessible equivalents available for purely wheeled or legged robots such as such as the Stanford Pupper [1] and OpenQuadruped [2]. Therefore, the creation of a robot that is low-cost, small scale, and easy to assemble would be important for the proliferation of technologies. Wheely, a lightweight, low-cost, and hybrid wheeled-legged quadruped robot, is the solution. Wheely allows for an accessible way of experimenting with wheeled-legged robots impossible in the status quo through the use of more economic electrical parts, a 3D printed frame, and open loop gaits generated using Bezier curves [3]. The aim of this research is to create a low-cost, accessible, wheeled-legged quadrupedal robot for the expansion of aformentioned technologies.

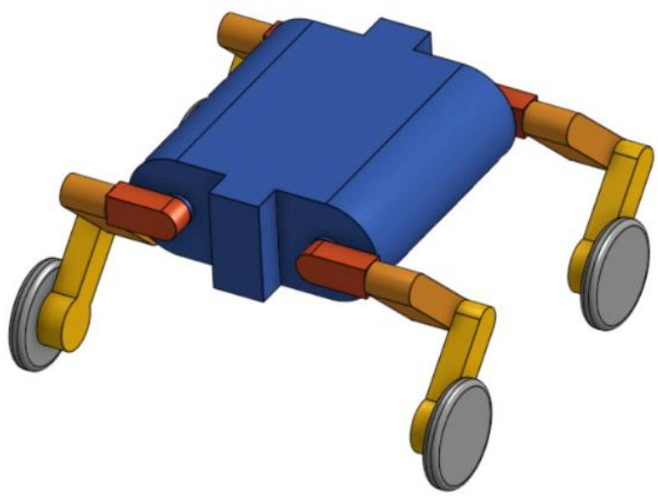

Fig. 1. CAD diagram of Wheely

A. Literature Review

A significant amount of work has gone into mobile legged and wheeled robots in recent years with advances in numerous organizations across the globe. This field has grown immensely in past few years with the introduction of many new mobile robots all with varying capabilities and characteristics.

a) Wheeled-Legged Quadrupedal Robots

Although most research regarding mobile robots is focused on wheeled or legged robots exclusively, there have been considerable advancements in recent years around hybrid wheeled-legged quadrupedal robots. These have been mostly large robots aimed more towards industrial or commercial use. Notable wheeled-legged robots include ANYmal [4-8], RoboSimian [9-10], Centauro [11], Sherpa [12], MAMMOTH [12], and Rollin' Justin [13], among others. ANYmal is a robust legged quadruped that can be modified to become wheeled-legged. It features omnidirectional movement and significant agility in indoor and outdoor environments [4]. RoboSimian is also very advanced, being able to surmount obstacles three times its wheel radius [10]. In addition, the Centauro robot can carry objects using its hands; teleoperated by a human in a haptic suite allowing for extra care [11]. However, all three are incredibly expensive with ANYmal, the smallest, being priced at more than $100,000 [4]. These advancements have yet to be made easily accessible to the public due to factors such as cost, size, and complexity.

b) Wheeled-Legged Bipedal Robots

Wheeled-legged bipedal robots are also a growing field with Handle [14-16] and Ascento [17-18] being two of the most notable. Handle, by Boston Dynamics, is a bipedal wheeled-legged robot capable of handling warehouse materials and traversing difficult terrain such as a snow-covered hill or stairs [15]. Ascento is a much smaller bipedal wheeled-legged robot weighing 10.4 kg with remarkable jumping capabilities, being able to jump 0.4 m off the ground [18]. Ascento can jump over obstacles, roll at considerable speeds across flat surfaces, and is robust when facing rough terrain [17].

c) Low-Cost Legged Quadrupedal Robots

Quadrupedal legged robots have been in development for much longer than wheeled-legged robots with several being relatively low cost. Low-cost robots such as the Stanford Pupper [1], OpenQuadruped [2], and the MIT Mini Cheetah [19] are several orders of magnitude more economic compared to expensive norm apparent in ANYmal [4].

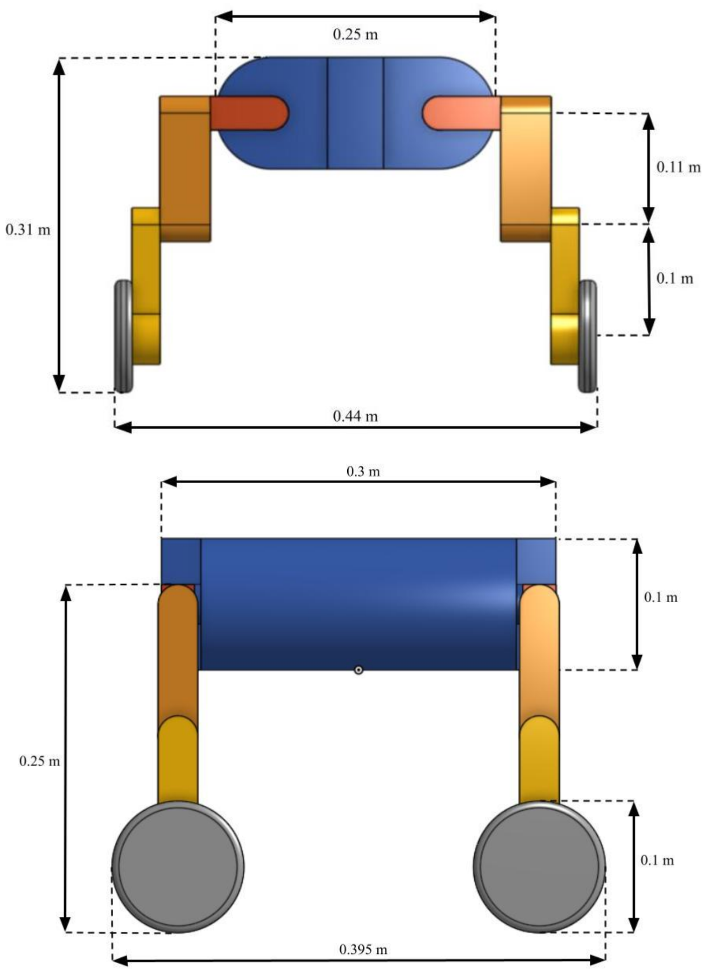

Fig. 2. Front and side views of Wheely with dimensions

II. DESIGN

The mechanical design of Wheely has been made to be as simple as possible for easy assembly and minimal cost. The robot can move in all degrees of freedom while using servo motors. The central body is roughly 0.3 meters long and 0.25 meters wide with a maximum leg length of around 0.25 meters. The leg motors are easily accessible servo motors for minimal cost and ease of acquirement. The wheels utilize economic stepper motors for the same reasons.

A. *Actuators*

Wheely uses the same actuator on every joint. Each actuator contains only one part, a Dsservo DS5160 Servo Motor. Using identical actuators simplifies robot design which allows for simplified acquisition, modification, and repairs for Wheely. In addition, the low-cost nature of servo motors makes it significantly cheaper compared to custom made actuators on other quadrupeds such as the MIT Mini Cheetah [19] or ANYmal [4]. The servo motors used by Wheely cost around $36 each, meaning leg actuator costs totals to around $432. This is a mere 12 % of the total leg actuator cost for the Mini Cheetah which totals around $3600 [19]. In addition to the three servo motors per leg, Wheely also uses four stepper motors to drive its wheels. 28BYJ-48 servo motors are extremely common and are sold off-the-shelf at around $4 a piece. This means that total actuator costs for Wheely is within $450.

In terms of actuator power, Wheely's servo motors generate a maximum of 6.86 N-m of torque which is more than enough to carry the chassis, motors, and control systems which weigh around 3kg. The DS5160 Servo Motor also features turning speeds of up to 8.06 radians per second. These motors are connected directly to the limbs for simplicity and flexibility. They are position controlled via pulse width modulation (PWM) and have an internal gearbox with a ratio of 1:279.

Fig. 3. Internal gearbox of DS5160 servo motor [20]

B. *Mechanical Design*

Wheely's four identical legs were designed to maximize simplicity and minimize costs, while maintaining a large range of motion. There are three servo motors per leg with one placed within the central body and two placed within the upper leg segment. The leg joints are mutually exclusive in range, allowing for 360-degree motion on the knee and the hip motor joint and 180 degree motion on the abduction/adduction joint. This is possible by making the upper and lower legs parallel but offset by approximately five millimeters which is used to house the motor arm. However, the servo motors limit joint rotation to 270°; this issue with having a limited motor range of 270° can be surmounted by changing the leg mounting between desired stances. By changing the motor alignment, the joints can reach any possible 270° subset of the 360° maximum. This feature allows Wheely to achieve all kinds of stances using different height settings, step clearance heights, and more. Wheely's body can move on six degrees of freedom with each leg having four degrees of freedom. At the end of each leg, there is also a stepper motor which drives wheels that are 10 cm in diameter that accounts for the fourth degree of freedom. This totals to 16 degrees of freedom which effectively allow Wheely a great deal of flexibility in gaits and stances. The entire body of the robot is made with PLA filament for easy replication and low cost [1,2, 21]. The low density of the PLA filament is also a plus factor as it allows the robot to be light, while maintaining structural integrity.

C. Electronics and Control

1) Control Hierarchy

Locomotion and other high-level control tasks are executed on a Raspberry Pi microcomputer [22]. Wheely employs a two-layer control hierarchy to modulate code and components. The RPi acts as the central command, while Arduinos [23] communicate with the Raspberry Pi through a serial connection and control motors based on inputs from the Raspberry Pi. The Arduinos act as a relay between the gait control and the actuators. Data logging is accomplished using an external web server that communicate with the Raspberry Pi through WIFI. Higher control runs at 1 kHz while motors operate at 300 Hz.

2) Motor Control

The servo motors are controlled via pulse width modulation; they acquire information based on the pulse length of a voltage wave. The stepper motors are each controlled by a ULN2003 Stepper Motor Driver Board which is fed information by the Arduino as well.

3) Gait Generation

Similarities between OpenQuadruped [2] and Wheely, allow for Wheely to use the same control algorithms [3] as OpenQuadruped with changes to its physical parameters and gait settings. This allows for quick and reliable gait generation without the need for a particularly strong computer to process it. All gait generation is processed on the robot using a Raspberry Pi, which is an economic and lightweight microcomputer. In terms of processing power limitations, it has more than enough for gait generation and data collection from potential sensors, among other sources of processing.

D. Wheeled Design

Wheely is designed to be a simple and accessible entry into wheeled-legged robots. The wheels are run off a stepper motor. This achieves the goals of simplicity, cost efficiency, and ease of access by operating on minimal resources to the maximum effect. Each motor can run at high speeds and lock in place for both driving and walking. Four such motors are used and are connected to wheels 10 cm in diameter. Each stepper motor features 3.43 N-m of torque and continuous driving capabilities. These motors allow Wheely to reach a maximum speed of 0.09 meters per second.

III. EXPERIMENTS

Wheely has been tested in a variety of ways in general locomotion. Wheely is capable of walking on flat surfaces independently and over small obstacles. Because of its relatively slow motor turn speeds, Wheely maintains a swing period of 1 second along with a clearance height and step length of 5 cm. Trials were done in simulation [24] using Pybullet [25].

A. Stair Climbing

Wheely is able to climb stairs that are 5 cm tall or 25% of its normal body height while being completely autonomous. Wheely is capable of driving over small steps less than 2 cm or 10% of its body height, but needs to switch to legged locomotion when faced with larger obstacles. Wheely normally operates at 20 cm tall.

TABLE I. WHEELED VS LEGGED MAXIMUM CLEARANCE HEIGHT

H=20 cm	Clearance Height (cm)	Body Height Percentage
Legged	5	25
Wheeled	2	10

B. Speed

Wheely's maximum speed when using legged locomotion is 0.04 m/s and 0.09 m/s when using wheeled locomotion. There is an approximate 110% increase in speed between legged and wheeled locomotion on flat terrain. However, when faced with rougher surfaces, the speed of wheeled locomotion goes down significantly.

TABLE II. LEGGED VS WHEELED SPEED AND ENERGY CONSUMPTION

	Speed (m/s)	Traveled Distance (m)	Average Torque (N-m)	Watts Per Meter (W/m)
Legged	0.044	2.66	46.4	17.4
Wheeled	0.093	5.60	64.9	11.6

C. Energy Use

Surprisingly, Wheely's energy use is higher when using wheeled locomotion. This is believed to be caused by the continuous holding of the ready position which is more strenuous than some other stances the robot may go through when walking. There is a 40% increase in energy expenditure between legged and wheeled locomotion, however, this is made up for by the 110% increase in speed previously mentioned. In terms of energy per meter, there is a clear increase in efficiency between legged and wheeled locomotion with them being 17.43 Watts per meter and 11.58 Watts per meter respectively. By taking speed into account, there is a 33.56% decrease in power consumption between legged and wheeled locomotion.

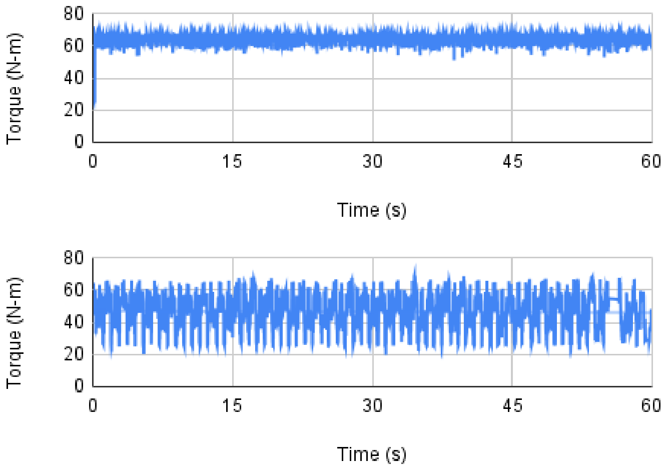

Fig. 4. Sum of legged and wheeled torque over one minute

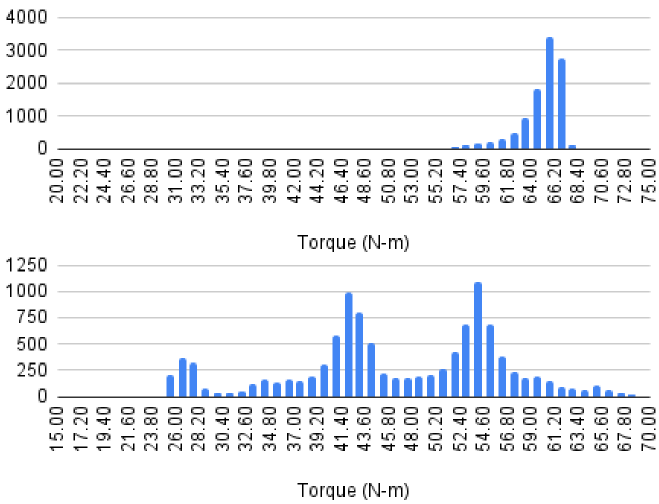

Fig. 5. Histogram of total torque over time for wheeled and legged locomotion

Wheely's energy use is much more varied when using legged locomotion causing a trimodal distribution of torque sums seen in Fig. 5. This is caused by four different gait phases visible in Fig. 6. Each gait cycle lasts roughly two seconds with two alternating plateaus, one in the low 40s and one in the low 50s. Each plateau is then connected by a dip down to the upper 20s.

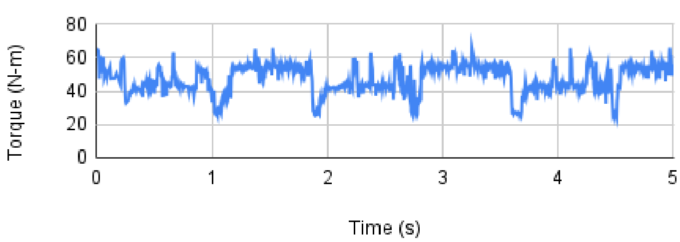

Fig. 6. Zoomed in view of torque useage over 5 seconds for legged locomotion

IV. Conclusions

Wheely is a new small-scale, low-cost wheeled-legged quadruped robot. It uses mass produced motors for ease of acquisition, simplicity, and cost effectiveness. Being a wheeled-legged robot, Wheely is capable of both driving and walking, which enables experimentation with new methods of locomotion using an economic platform. It can reach top speeds of up to 0.04 m/s when walking and 0.09 m/s when driving. It can climb steps 25% of its height using only open loop gaits and step over small obstacles 5 cm tall. Its wheels allow it to travel 110% of its top speed when walking. In addition, it is remarkably economic, totaling around $530 total for all parts.

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