Dynamic Robotic Leg

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Abstract

In this project we designed, built, and tested a robotic leg mounted on a development stand. The leg and stand system has three degrees of freedom with two actuated joints in the leg and one degree of freedom provided by a linear rail on the test stand which the leg is mounted to. The leg uses high torque, low cost, consumer-off-the-shelf brushless DC motors. The leg is comprised mostly of custom 3D printed parts and open source electronics. The leg is able to execute trajectories for walking gaits and jumping through an inverse kinematics controller using PID position control. The development stand powers the leg using two modified server grade power supplies and allows for safe testing through multiple emergency-stop buttons and a circuit breaker. We have also created a simulation for trajectories to be developed with and tested in before implementing them on the physical leg.

Contents

1. Introduction

While wheeled robots excel in flat terrain, they still face challenges with navigating a world created for humans [1]. Similarly, aerial robots suffer from difficulties such as moving through confined spaces and interacting with the environment around them. The problem of navigating multi-level environments, including stairs and unstructured environments such as a floor with debris or uneven terrain, has not been fully solved with ground robots. Although aerial robots have been deployed in these situations, they face many obstacles as listed in page 172 of [2]. Legged robots, such as quadrupeds, are able to successfully navigate a multitude of human-oriented environments without the restrictions imposed by aerial and wheeled vehicles. Specifically, dynamically stable quadrupeds hold a great deal of promise for navigating unstructured environments because of their large workspace, ability to reject disturbances quickly, and the flexibility in movements they can perform. Far more research must be conducted before legged robots will be useful in real world deployment. Currently, there is no existing open source platform which researchers are able to use to develop algorithms for legged robotics.

We have created a two degree of freedom robotic leg stabilized on a test frame in order to demonstrate trajectories used for walking gaits. This project demonstrates the feasibility of inexpensive walking robots through a fully functional leg and test rig that can easily be reproduced with consumer off-the-shelf components and built upon to provide the starting point for a novel quadrupedal robot. We will provide an open-source design including all necessary structural components, a complete bill of materials, and necessary software to control the leg. It is our hope that this project can serve as the base for future research projects expanding on dynamic leg control and its applications by providing a ready-to-build leg that handles all low-level control internally.

1.1 Objective

While research labs and companies have been developing dynamic legged robots for years— Boston Dynamics' Spot mini [3], Unitree's Laikago [4], Ghost Robotics' Vision [5], MIT's Cheetah [6], etc— all of these robots use custom motors and/or proprietary control algorithms which are not conducive to increasing the development of legged robotics. Each of the quadrupeds listed above started as a single leg tested on a stabilized platform before integrating the leg into the entire robot. Currently, when developing a new legged robot it is necessary to develop a custom leg as a starting point much like the examples listed above. With a fully open-source, sub one-thousand dollar dynamic robotic leg and controller, we believe we can accelerate the development of legged robotics by reducing entry barrier both technically and financially to increase involvement in the field.

2 Design

Figure 1: Full Project 3D Model. Development stands based on stands depicted on page 82 of [7] and page 300 of [8].

The design of the dynamic robotic leg can be divided into three distinct but highly connected categories. First, we designed the mechanical components of the project such as the leg links, ganty, and development stand. Second, we created a mathematical model and simulation for the leg to determine the necessary operating range of the motors. Third, we designed the electrical system based on our expected power and torque requirements.

2.1 Simulation

When designing the simulation, we started by creating an inverse kinematic controller for the leg. Since the leg has only two joints, we used a geometric approach to deriving the inverse kinematics equations.

We found that given a coordinate within the leg’s workspace, the joint angles could be calculated using equation 1 and equation 2.

$$q_2 = -cos^{-1}\left(\frac{x^2 + y^2 - a_1{}^2 - a_2{}^2}{2 * a_1 * a_2}\right) \tag{1}$$

$$q_1 = atan2(y, x) + atan2(\, a_2 * sin(q_2), a_1 + a_2 cos(q_2)\,) - q_2 \tag{2}$$

Equation 1 and Equation 2 allow us to transform trajectories created in cartesian space into the configuration space of the leg, where q_1 and q_2 are the hip and knee joint angles respectively, a_1 and a_2 are the upper leg and lower leg link lengths respectively, and *x* and *y* are the coordinate of the foot with respect to the body frame of the leg.

After deriving the inverse kinematics equations, we created a script in MATLAB that generated trajectories in the configuration space of the leg based on desired *(x,y)* coordinates of the foot over time. We then created a Simulink model shown in Figure 2 which uses Simscape multibody to simulate the physics of the leg. The simulation contains PID position controllers for each joint and allows the user to input a trajectory and plot the required torque at each timestep for executing the trajectory.

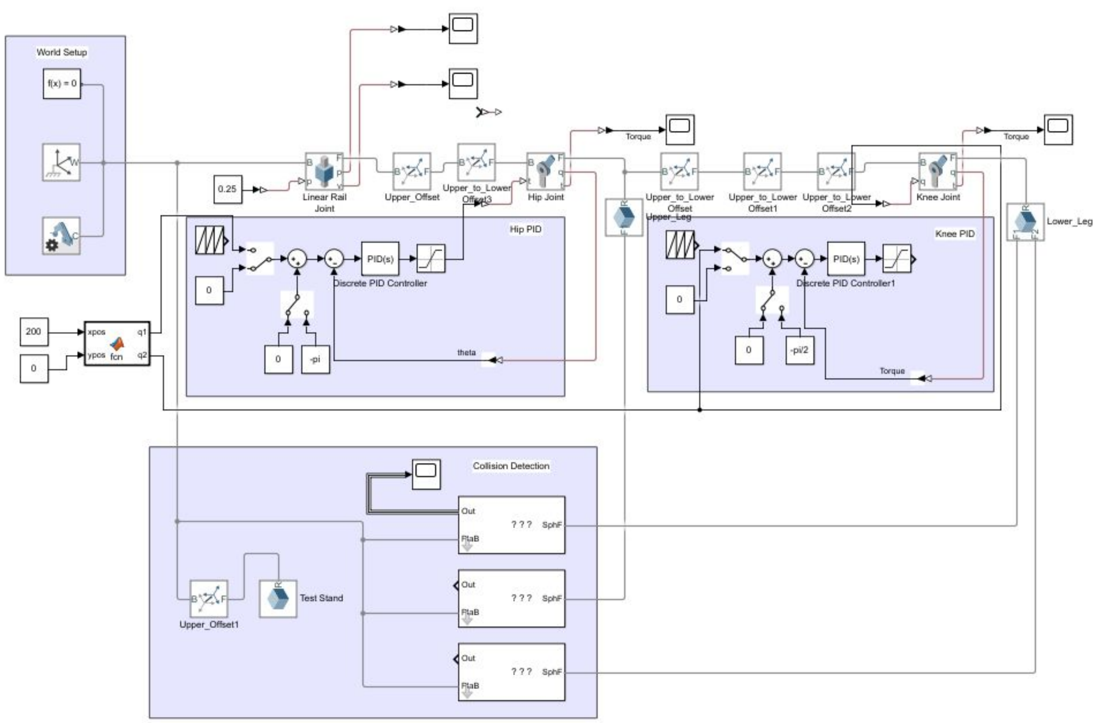

Figure 2: Simulink Block Diagram using Simscape Multi-Body. Simulates the full system with inverse kinematics controller using independent joint PID position control. Allows plotting of joint torque and position data

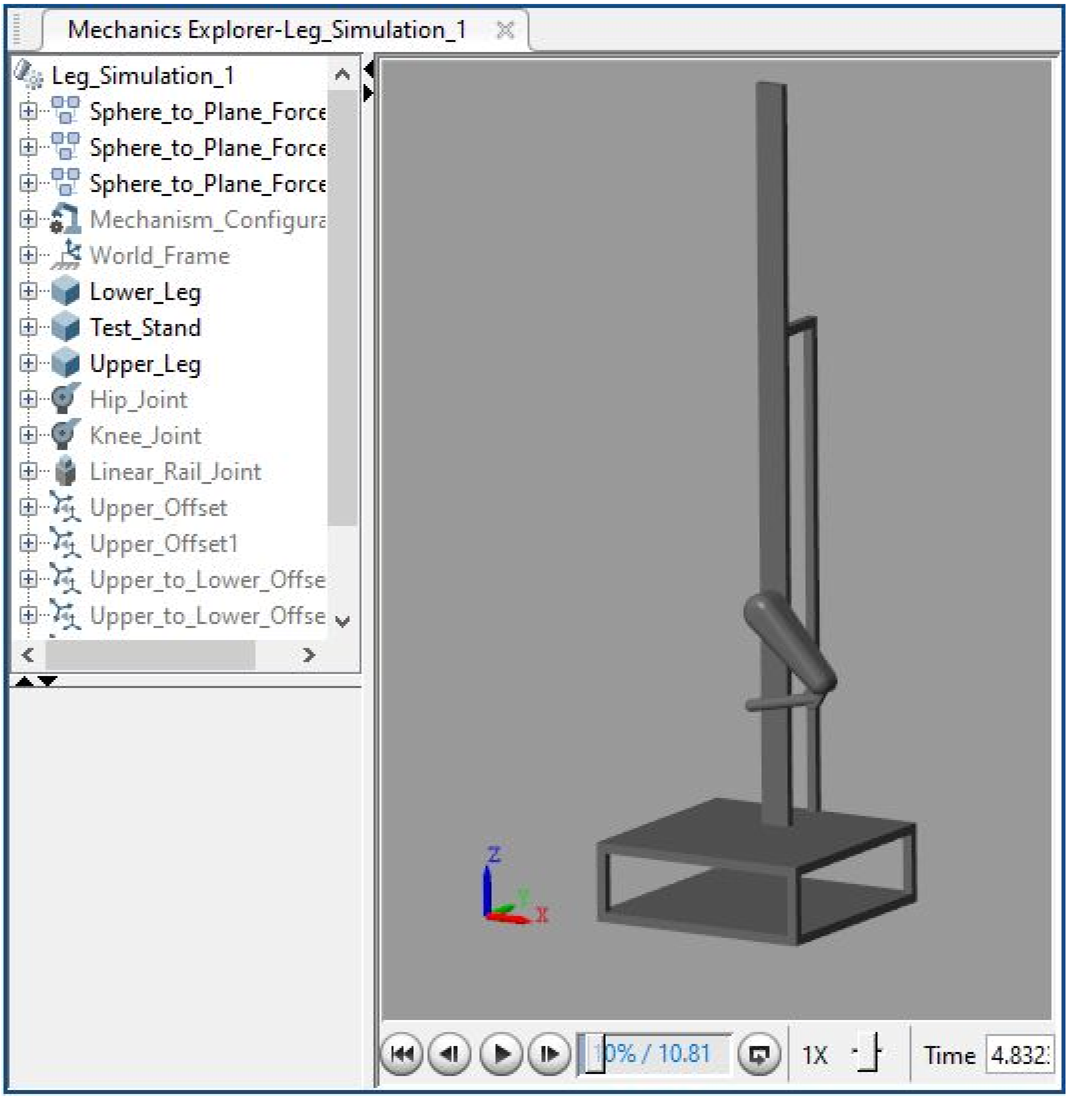

Figure 3: Physical model of the simulation generated by SimScape Multibody. Manipulations to SIMULINK block diagram update while simulation is running allowing for efficient development of trajectories and live tuning of controller gains

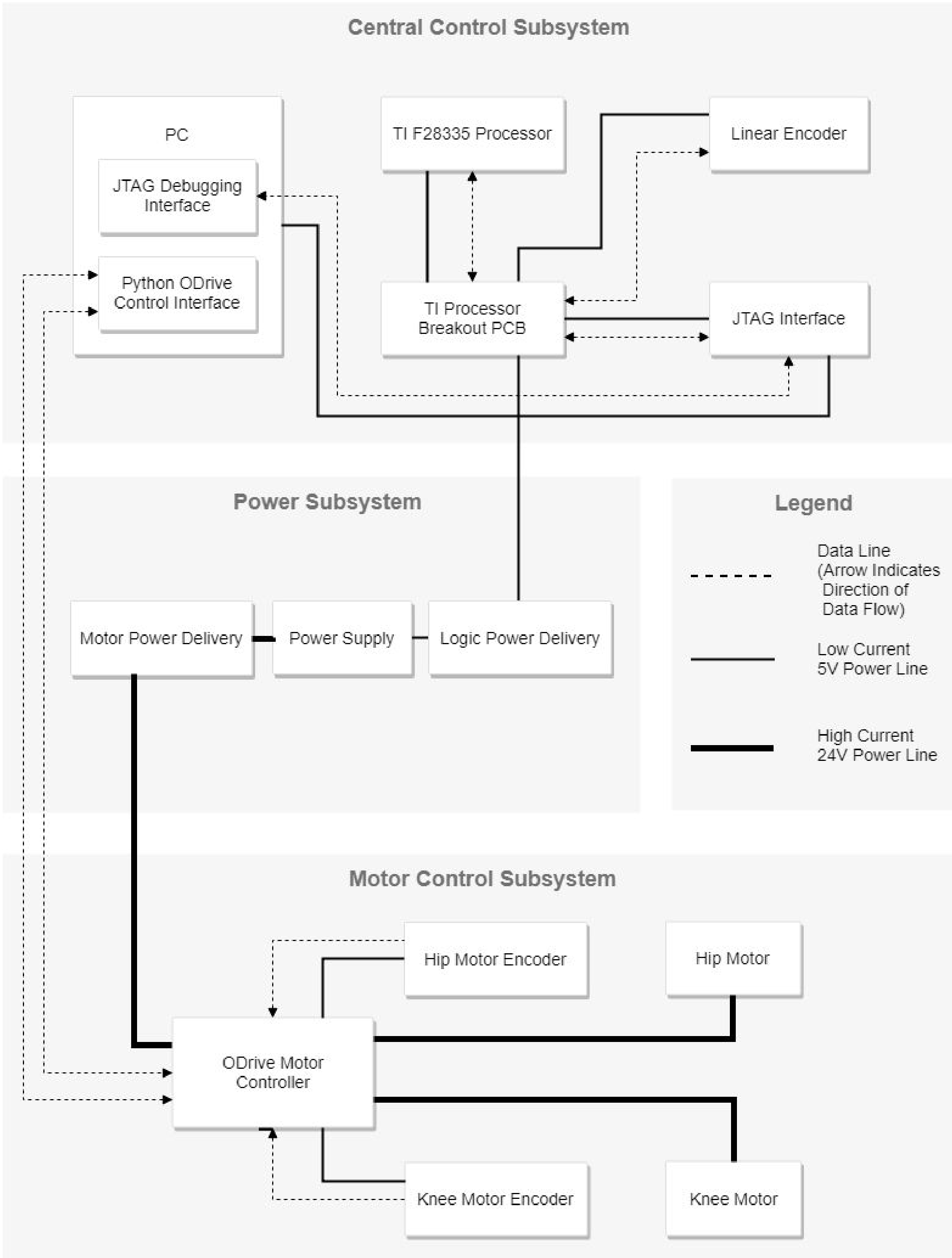

Figure 4: Full System Block Diagram

2.2 Power Subsystem

The power subsystem consists of three modular components, the power supplies, the logic power delivery, and the motor power delivery. These three components work together to reliably meet the high power demands of our project.

2.2.1 Power Supply

Two 12 volt, 750 watt server grade power supplies are connected in series to provide a maximum of 1500 watts at 24 volts. A relay board controls the power supply's operation for safety and ease-of-use.

2.2.2 Logic Power Delivery

The logic power delivery system consists of a wiring harness to connect the power supply to the Processor Breakout PCB as well as a 5 V switching regulator on the PCB to power the TI DSP.

2.2.3 Motor Power Delivery

The motor power delivery system consists of a wiring harness to connect the power supply to each motor controller board as well as a 60 A circuit breaker to provide overcurrent protection.

2.3 Central Control Subsystem

2.3.1 TI F28335 Digital Signal Processor

We use the TMS320F28335 controlCARD to record the height of our leg through the hardware quadrature encoder input.

2.3.2 TI F28335 Breakout PCB

The Breakout PCB provides connections to all necessary GPIO on the ControlCARD and provides power regulation and protection to the processor. The board provides a 20-pin JTAG connection for programming and real time debugging.

2.3.3 Height Sensing Encoder

We use an incremental encoder to measure the movement of a belt loop attached to the gantry to track the height of the leg. The encoder has a resolution of 2000 CPR, and reads the orientation of a magnet mounted on a 20 tooth pulley, spun by a 2 mm pitch timing belt. This results in a sensing precision of 0.02 mm.

2.4 Motor Control Subsystem

2.4.1 Motor Controller

Each motor is driven by an ODrive motor controller. The ODrive controls the position, velocity, and torque of each motor.

2.4.2 Motor Encoders

We use absolute magnetic encoders with a precision of 2000 CPR to measure the rotation of the motors. The encoders connect directly to the ODrive for providing feedback for the PID position controller as well as rotor position data for the Field-Oriented-Control algorithm.

2.4.3 Motors

Motor selection was integral to the success of our project. We selected two 6354 brushless DC (BLDC) motors. These motors were selected for their high torque capabilities, 0.16 Nm/A, and large current rating of 2450 W.

3. Design Verification

The verification of our project was ultimately a full-system test of the dynamic leg including tasks such as trajectory following and jumping. To ensure our project was fully functional when completed, we made use of modular design and unit testing, verifying each component individually before integrating it into the larger system.

3.1 Power Subsystem Verification

3.1.1 Motor Power Delivery

While modifying the power supplies to output between 23.7 V and 24.7 V when connected in series, we used a multimeter to ensure that the output voltage of each power supply individually was outputting the required voltage. After finding that the voltage of each power supply was different, we used the internal voltage adjustment potentiometer to adjust the output voltages to each be exactly half of our desired output voltage. We found that the cooling fan running at full speed dropped the output voltage of the supplies by 0.03 V. We accounted for this drop during adjustment as well as anticipated voltage drops due to the high current pulled by the joint motors by setting the output voltage to 24.4 V.

3.1.2 Logic Power Delivery

After connecting the F28335 Breakout PCB to the power supplies, we tested the voltage output of the on-board switching voltage regulator. We found that the voltage remained steady at 5.26 V, which is in our required operating range.

3.2 Central Control Verification

3.2.1 Leg Height Sensor

Verification of the leg high sensor was sufficiently complex. We designed a belt system anchored to the gantry with a pulley on the top and bottom of the development stand. When the leg moves, the anchored belt rotates the pulleys. A magnetic encoder can then read the rotation and angle of the shaft on the lower pulley, thus giving the height of the leg at any given time. The challenge of this verification was, given the high pulse count of the encoder, normal encoder polling techniques failed to capture a number of pulses when the leg moved quickly (i.e. jumping). To remedy this, we used the hardware quadrature encoder reading implementation embedded in the TMS320F28335 controlCARD. This allowed us to read the encoder's impulses entirely using hardware and thus was fast enough to keep up with the exceptionally high pulse rate. We verified our accuracy by moving the gantry up or down a known, measured amount, and checking the resulting encoder output to ensure it was accurate.

3.2.2 F28335 Breakout PCB

The F28335 Breakout PCB was designed to provide convenient, low cost connection to the F28335 ControlCARD. As previously mentioned, we verified the voltage provided by the on-board regulators. The steady 5.26 V output was within our design tolerances. Additionally, we verified the JTAG breakout worked as intended, allowing us to use the SEGGER J-LINK as a JTAG interface between the ControlCARD and our computer.

3.3 Motor Control Verification

3.3.1 Motor Controller Board

One key aspect of the motor controllers we selected was its ability to output 35 A continuous current. We set up our motors to pull 35A continuous current and verified that the controller functioned as intended, while remaining under 50 °C.

3.3.2 Motor Encoders

In order to get accurate, closed loop positional feedback, we needed to verify the accuracy and reliability of our encoders. We rotated the motor's shaft a known angle and compared this against the angle reported by the encoder. The resulting difference was within our tolerance of 0.25 degrees of the true angle.

3.3.3 Motors

The final aspect of our motor control was the motors themselves. To verify our motors would function reliably, we ran 30 A continuously through them, ensuring the motors remained below 65 °C. We also verified the motor's torque output, first in the datasheet, and then using a luggage scale to read the force it could apply.

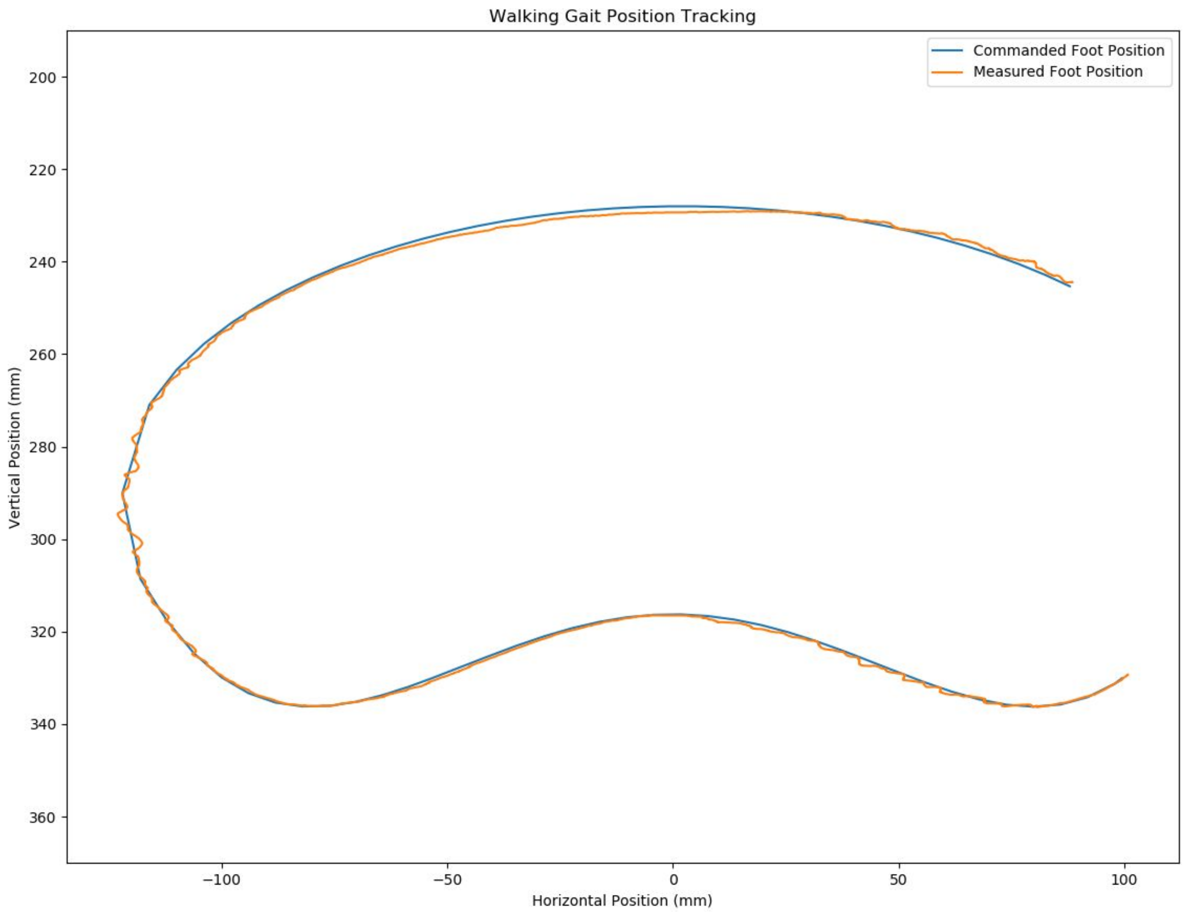

Figure 5: Position Tracking of Walking Gait Trajectory

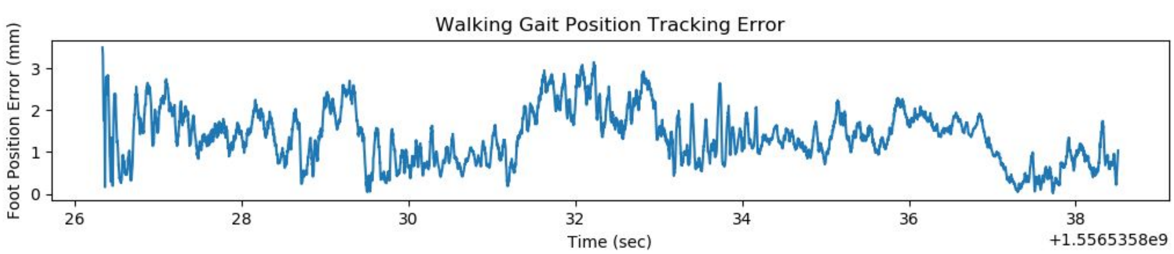

Figure 6: Tracking Error during Execution of Walking Gait Trajectory

4. Costs

4.1 Parts

Table 1: Project Cost

Part Name	Description	Manufacturer/Supplier	Quantity	Unit Cost	Total Cost
TMDSCNCD28335	F28335 ControlCard	Texas Instruments	1	$69.00	$69.00
ODrive	Motor Controller	ODrive Robotics	1	$119.00	$119.00
6354 60KV Motor	Brushless Motor	E-Power Hobby	2	$90.00	$180.00
AS5047D	Magnetic Encoder	DigiKey	3	$16.76	$50.28
Central PCB	Regulator/data routing PCB	PCBWay	1	$5.00	$5.00
3D Printer Filament	PLA Filament	Hatchbox	2	$24.00	$48.00
Knee Axle	1/2 Inch Hex Shaft	Vex	1	$11.99	$11.99
Bearings	1/2 Inch Hex bearing	Vex	6	$2.99	$17.94
Motor Mounting Screws	M4x12 Screws	Amazon	1	$3.99	$3.99
T-Slot Extrusion	10 x 1m T-slot 2020	ZYLTech	1	$49.99	$49.99
T-Slot Angle Brackets	12 x Angle brackets	ZYLTech	2	$6.95	$13.90
Power Supply	2x 12v 750w Server Power supply	Dell / Ebay	1	$27.99	$27.99
T-Slot wheels	10 x T-slot wheels for gantry	Amazon	1	$7.99	$7.99
SEGGER J-LINK	JTAG Debugger	Segger / Mouser	1	$60	$60.00
			Total Robot Cost:		$665.07

4.2 Labor

Table 2: Labor Cost

Team Member:	Hourly Wage	Weekly Hours	Number of weeks	Multiplier	Cost per Member
Joseph Byrnes	$35.00	30	12	2.5	$31,500.00
Ahsan Qureshi	$35.00	12	12	2.5	$12,600.00
Kanyon Edvall	$35.00	12	12	2.5	$12,600.00
				Total Labor Cost:	$56,700.00

5. Conclusion

5.1 Accomplishments

Our project exceeded expectations in terms of accuracy and jumping height. The leg is capable of jumping over 20 cm. We successfully implemented an inverse kinematic controller based on independent joint PID position controllers. The controllers allow the leg to execute various movement trajectories such as walking and running gaits, while staying within 3.5 mm of the target end effector positions. We were able to accomplish these goals while only using 3D printed parts and off-the-shelf components.

5.2 Ethical considerations and Safety Hazards

Within our project, there are several potential safety hazards.The first concern that we will deal with is disabling the robot leg if it begins to move unexpectedly. To mitigate this issue we included emergency stop buttons which disable power to the motors. Additionally, our motor controllers have a failsafe enabled that disables the motors if no communication is received after a predetermined number of missed packets or time. Another safety hazard that we considered is the inclusion of high wattage power supply units within our design. Continuously drawing a high amperage may overload lab circuit breakers and power supply connections can be hazardous if not enclosed properly. We included a power dissipation resistor to prevent the regenerative current of the motor from damaging the overall electrical system of the robot or power supply units. Additionally, we added 3D print protective enclosures to ensure all exposed connections were properly covered.

A robotic leg by itself does not prove to have ethical challenges, however, once the leg is applied to a mobile platform, it may present ethical challenges. Isaac Asimov founded the idea of robots and established the Three Laws of Robotics, being 1) A robot may not injure a human being or, through inaction, allow a human being to come to harm; 2) A robot must obey the orders given it by human beings, except where such orders would conflict with the First Law; and 3) A robot must protect its own existence as long as such protection does not conflict with the First or Second Laws [09]. An autonomous mobile platform could be designed using our legs which could be used as a mount for a weapon, or as a vehicle to perform illegal surveillance. These acts would violate the IEEE code of ethics, specifically, code 1 and code 9 [10]. We would prevent our designs from being used for harmful purposes by withholding our leg and technology associated with it from the public sphere. We would vet potential consumers of our product so that we can prevent it being used for purposes we find to be in violation of our ethics. At the same time, our research could be used for positives as well. For example, having met with officers of the UIPD, we have discussed future applications of our robotic leg such as the integration of the leg onto a mobile reconnaissance platform. This platform would provide increased safety to the officers by distancing them from potential threats such as explosive devices or hidden suspects.

5.3 Future work

Currently, we have implemented a position based controller, but we plan to develop a dynamic task space controller because it provides increased control and superior tracking when executing trajectories. We will be releasing our entire project as an open source platform for legged robotics research and education. We will be continuing to develop the JoeDrive BLDC motor controller and releasing it as an open source addition to the ODrive project. We also envision that the leg could be incorporated into a platform with multiple legs in future work by ourselves or users of the open source project.

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Appendix A Requirement and Verification Table

Requirement	Verification
Power Supplies	
Provided voltage must stay between 23.7V and 24.7V	Use a multimeter to confirm that the output of the power supply stays within 23.7V and 24.7V during 30A operation of each motor.
Must provide a minimum of 15A continuous current per motor. At 24V, this corresponds to a maximum power output of 1500W	Set both motors to draw 15A continuously and confirm with a current probe that at least 30A is being supplied to each motor.
Motor Power Delivery	
Use wire that does not cause a voltage drop of more than 1.5% of the power supply voltage.	Measure voltage drop across the power cables using a multimeter and confirm that drop is below 1.5% of power supply voltage.
Logic Power Delivery	
Use wire that does not cause a voltage drop of more than 1.5% of the power supply voltage.	Measure voltage drop across the power cables using a multimeter and confirm that drop is below 1.5% of power supply voltage.
Central Control Processor	
Must be able to perform all dynamics calculations for our controller in less than 1 millisecond.	Output a 0v signal through an output of the processor when the calculations are finished and set the signal to 5v when the periodic task starts again. Confirm using an oscilloscope that the processor is not being overloaded by measuring the duty cycle of the signal, confirm duty cycle is under 1ms.
F28335 Breakout PCB	
Board must continually supply 4.9 to 5.5 volts to the ControlCARD.	Using a multimeter, read the voltage at the output of the regulators when leg is stationary and when 30A per motor is being supplied to ensure regulators are not affected by voltage sag due to the the motor power system. Verify the voltage reading is between 4.9V and 5.1V.
Regulators must stay below 50°C for at least 30 minutes of operation under room temperature	Using an infrared thermometer, measure the temperature of the regulators after 30 minutes of operation.

Must breakout the ControlCARD's JTAG interface for programming using an Atmel ICE programmer.	Connect PCB to a computer using Atmel ICE programmer and confirm proper firmware upload and debugging communication by setting a variable in real time through the Code Composer Studio expressions interface. Confirm variable has changed as expected.
Must provide USB access to the ControlCARD's serial interface.	Connect ControlCard to PuTTy Terminal and confirm debugging data such as joint angle sent through USB Serial port is functioning.

Height Sensing Encoder

Must measure robot height with accuracy of at least 2mm	Using calipers, move the leg up and down by 1mm at a time and record distance travelled reported by the encoder/processor. Readings are considered good if measured distances is within + or - 1mm of manually measured distance.
Must report distance travelled with a frequency of at least 1ms.	Connect encoder to oscilloscope and measure frequency of data output. Ensure period is less than or equal to 1ms.

Motor Controller

Must support current sensing hardware to achieve torque-based control. Current sensing must be accurate to 5% of actual value.	Using an ammeter, measure current draw on motor power lines. Confirm that measured value is within 5% of the motor controller sensed value.
Must support current output control to achieve torque-based control. Current output must be accurate to 5% of set value.	Using a high-precision lab scale confirm that the torque output from the joint is within 5% of the set torque value.
Must deliver a minimum of 30A continuous current for 30 seconds without rising above 50°C.	Use an infrared thermometer to measure the heat being radiated from the MOSFETS in the motor drive circuit, record and plot the data over the period of 60 seconds of continuous operation. Simultaneously, use a non contact multimeter to measure the current provided to make sure it is 30A for the entire operation.

Motor Encoders

Must report angle within 1 degrees of true angle.	Connect the encoder to a stepper motor and rotate the shaft for a known amount of steps for one full rotation. Record the position data from the encoder and confirm that the encoder reports the angle within 1 degree of the true angle throughout the entire rotation.

Must have data output frequency of 1000 Hz or greater to achieve joint angle updates every 1 ms.	Connect encoder with counter interface to an oscilloscope and measure frequency of data output. Ensure period is less than or equal to 1ms.

Motors

Must allow for up to 30A continuous current for 30 seconds without damaging the motor coils or raising the temperature of the plastic enclosure above 65°C.	Using an infrared thermometer, measure the temperature of the enclosure after 10 minutes of operation. Ensure it is below 65°C.
Must have a torque constant of at least 0.05Nm/A.	Using a spring scale or digital luggage scale, confirm that the torque output from the joint is at least 0.05Nm when 1A is applied.
Must be less than or equal to 63mm in diameter and less than or equal to 90mm long to fit in motor housing.	Measure the motor using calipers with a precision of at least 1/10 mm.