August 2018

RoboDog

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RoboDog

A Major Qualifying Project Report:

submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

by

______________________________

Michael Steidel

August 7, 2018

Approved:

______________________________

Professor Marko Popovic, Major Advisor
Abstract

Many robots used for navigating and exploring are wheeled robots. These robots are frequently used as they are typically cheaper and have greater maneuverability. However, legged robots offer many unique advantages over wheeled robots. They can traverse rough terrain that can present obstacles to wheeled robots. Unfortunately, the disadvantages of legged robots, such as their difficulty to design and control and their high production costs, make them less appealing. The goal of this project was to demonstrate the feasibility of making a low-cost, legged robot by expanding on work previously done on a robotic quadruped. While many of the new elements added to this robot functioned properly, the culmination of many problems prevented this project from making a significant amount of progress.
Acknowledgements

This project would not have gotten as far as it did without the aid of sophomore students Caleb Wagner, Ryan Eastwood, and Ben Liang. They were a constant source of help even with their regular and sometimes extended course loads. I also need to thank Andrew Lewis, another senior student who performed his MQP with Professor Marko Popovic as his advisor, for 3D-printing parts for me for relatively cheap. His help saved a significant amount of time and money.
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Executive Summary

This project report is an examination of the work done redesigning and reconstructing elements of an already existing robotic quadruped as well as the testing of the elements. This report also includes a brief summary of the work done by the team that had worked on this quadruped the prior year. Encompassed in this report is a review of the steps taken in order, with a review of the previous project, to brainstorming and goal identification, to designing and assembling the new components, and finally to programming and testing.

The legs of the robot were redesigned, while the torso made of extruded aluminum framing known as 80/20 was retained. Two new leg designs were tested, one of which was a major redesign that used carbon-steel tubes and 3D-printed parts and the other of which incorporated new components into the older design. The main feature of this project is the series elastic actuators that are used to manipulate each of the lower legs.
1 Introduction

In the field of robotics engineering the majority of mobile, autonomous robots use wheels to achieve motion. In controlled environments, in which humans are present to right any problems that might arise, these are usually sufficient. However, with the use of mobile, autonomous robots becoming more widespread, they begin to encounter more and more scenarios that are difficult for them to overcome. This is especially evident in situations involving environments that are unexplored or consist of rough or unstable terrain. When encountering a significant obstacle, a wheeled robot must maneuver over or through it or find a path around it. If neither of these are possibilities, then the robot cannot continue on its path. In the case of a legged robot, the robot may simply be able to step over the obstacle and ignore it.

To combat these issues, many groups have spent several years, and even decades, researching and developing legged robots for use in these circumstances. However, designing and constructing even just one of these robots is typically a long and expensive process. Additionally, while great strides have been made in improving these robots in recent years, they are still not extensively used and are not often seen outside of the lab.

This project was carried out by a senior undergraduate student at WPI with a significant amount of assistance from three sophomore undergraduate students, one of whom had helped work on the previous year’s project. This report describes the processes we underwent during our time working on this project. It details the steps we took while attempting to reach these goals, from initial research, to design and construction, to testing. It also examines the many problems that were encountered, what areas we succeeded and failed in, and reflects on our methods and
how they could be improved upon, and proposes ways for future teams to improve upon our work.

The motivation behind this project was to improve upon an already existing quadrupedal robot and is effectively an extension of last year’s project. The design, construction, and programming of the existing robot was the result of a previous years’ project. This robot was intended to be able to walk over uneven terrain while still being relatively low cost. This earlier project was unable to meet all of its goals, as it was able to walk but not effectively over rough or uneven terrain. This project set out to rectify that.

As a part of this project we redesigned, reconstructed, and tested parts of a robotic quadruped previously designed and constructed. This project was intended to increase the mobility of this robot, by improving its ability to walk. This was aimed to be done by actuation of the legs via additional elastic systems and stronger servos. Through these efforts we hoped to further pave the way for low-cost quadrupedal robots and set goals for future teams to work towards.
2 Background and Research

The project began by examining the functionality of the robot achieved by the previous team and reviewing the report written by them as well. The previous year’s group did a large amount of background research regarding quadrupedal gaits, other similar robots, and the inverse kinematics of the legs which we were able to rely on while working on this project. This information proved to be invaluable to us. Using this information, we began identifying major problems that held back this project and evaluating potential further courses of action to solve these problems.

One problem with last year’s project was the fact the servos being used were barely strong enough to lift the legs off the ground and push the robot along. The previous servos were Savox SV-1270TG servos of which eight were used, one for each of the hip joints and one for each of the knee joints. While these servos are exceptional for smaller, personal projects they fall
short when used in more heavy duty projects. As a result, replacing these servos became our first priority. After much research and deliberation, we decided to replace the Savox servos on the hip joints with Dynamixel MX-64T servos. We chose these servos for a multitude of reasons. Not only could the Dynamixel servos provide much more torque than the Savox servos, they also provide many additional features that made them very appealing. These servos could easily be daisy-chained together so that all servos being used could be connected through the board through one port as opposed to having each individual servo being connected to a different port. The servos are also easily controllable using downloadable software, which made testing quick and simple. This mixed with a range of 360 degrees of motion and integrated magnetic rotary encoders that recorded the position of the servo to a 12-bit value made using them very convenient.
One of the key elements of last year’s project was a parallel elastic system. The servos themselves didn’t have enough torque on their own to hold up the weight of the robot. The parallel elastic system was implemented by the previous team in order to provide additional torque to assist the servos. As part of our research we looked into other potential ways to use elastics to improve the robot. During this time, we learned of series elastic actuators. Many standard actuators are stiff as a result of a motor or servo directly moving a load, whereas a series elastic actuator includes an elastic component somewhere between the motor or servo and the load. This reduces the stiffness of the component and allows for more natural motions. As
stiffness was a key problem the previous team experienced while attempting to get the robot to walk, we decided that a series elastic actuator would greatly help improve the motion of the legs and made it one of our key goals for this project.
3 Objectives

3.1 Primary Objectives

Four primary objectives were devised for this project to complete.

3.1.1 Servos

The first objective was to assess the effectiveness of the servos used by the previous team and to determine whether to supplement these servos or to simply replace them with more powerful ones. While straightforward, this was a key, early step towards improving the mobility of the robot.

3.1.2 Series Elastic Actuator

The next objective involved developing a series elastic actuator. This would be the signature feature of this project and was intended to solve many of the major problems with the previous design.

3.1.3 Locomotion

This objective can be broken up into three separate goals. The first of these was to program the robot able to walk at a steady pace of 0.7 m/s (~1.5 mph) on steady, even ground. This would have been followed by modifying the program to achieve a similar speed on moderately rough terrain, such as gravel or sand. Finally, we planned to have the robot walk up a slope of 20 degrees.
3.1.4 Balance

The final objective was to add an inertial measurement unit (IMU) to the dog in order to determine the orientation of the dog’s body with respect to the ground and to keep it level, while walking over terrain with little to no slope and prevent it from trying to walk up slopes that were too steep.

3.2 Future Objectives

Two additional goals were proposed. These goals were devised in the event that we met all of our goals in a timely fashion and for future project teams to consider.

3.2.1 Locomotion

The first of the goals was simply to improve the walking capabilities of the robot. This included increasing its speed on flat ground to 1.4 m/s (~3.0 mph) and to program it to walk up a flight of stairs.

3.2.2 Wiring

This objective would involve condensing much of the wiring into a custom circuit board. This would help remove many of the cluttered and tangled wires present.
4 Methodology

4.1 Design and Construction

The design and construction phase was defined by two distinct design attempts. The first attempt was complete overhaul of the existing design and was the design used for the majority of the time spent working on this project. The decision to switch to a different design was a result of significant flaws with the initial design.

4.1.1 Initial Design Attempt

The main focus of this project was the design and construction of new legs to replace the old ones. This process began by deciding how to best improve the motion of the legs. Our options ranged from adding supplemental servos to the current ones or replacing some or all of the current servos with more powerful one. We ultimately chose the latter option, as we felt that the other option would be much more cumbersome to implement. We also had to devise a way to mount these new servos. The previous upper servos were mounted to the outside of the frame of the robot. Due to the size and weight of these new servos this was not a viable option. Instead, we attached two lengths of 80/20 to the inside of the frame perpendicular to the front and back of the robot and 3D-printed mounts for the servos.
In order to actuate the leg, we designed and 3D-printed couplers that would be attached to the servos. Shaft collars would be placed inside of these couplers and would be tightened onto the axles. The normal set screws in these collars were replaced by longer screws that would project out through holes in the side of the coupler. This would ensure that the collar, and by extension the axle, did not slide inside of the coupler.
With the new servos implemented into the frame, the next step was to redesign the legs. This new design would be required to accommodate the new series elastic system. We decided to switch from using the thin, rectangular, aluminum legs to using hollow, carbon steel tubes for the legs. This decision was made with the idea that it would be easy, quick, and cheap to make 3D-printed parts that would fit on the tubes. We designed the leg to consist of three segments of tubing: two shorter segments would be placed parallel to one another to make up the upper leg and one longer segment that would sit between the shorter segments to act as the lower leg. The servos to actuate the series elastic system and therefore the lower leg would be mounted to each leg near the middle of the outer segment of the upper leg. One flaw with this design that was immediately apparent was the very small area of contact and low friction on tile floors. This was fixed by inserting rubber stoppers into the bottoms of the legs.
In order to actuate the upper leg, we used a chain and sprockets to connect the axle of the leg to the drive axle. The drive gear was a small 9-tooth sprocket and the driven gear is a larger 45-tooth gear. This provides a gear ratio of 5:1 and provides the leg with a 72 degree range of motion.

The next step involved redesigning the parallel elastic system. The old design involved a wedge-shaped 3D-printed part known as the “pi”. This part was attached to the axle of the lower leg that an elastic tube would be tied around in order to prevent the lower leg from bending due to gravity. This part was redesigned in order to fit onto the upper end of the lower leg and have rubber tubing tied between it and a protrusion on the servo mount. Two variants of this new pi needed to be designed, one design for the left legs and one for the right legs.
Figure 6 Original Pi with Elastic Tied to it
Of course, we had to design a way to implement the new series elastic actuator as well as the parallel elastic system into this design. For the series elastic system, we designed a spool that would be turned by the servo on the lower leg. An elastic would be wrapped around the spool and tied to two 3D-printed parts on the lower leg, one at the very top of the leg and one a bit further down. Originally, we had planned to use the same elastic tubing that the parallel elastic system. However, these proved to not provide enough tension to lift the leg. We then tried replacing the tubing with fishing line, a material with much lower elasticity and high tensile strength.
4.1.2 Second Design Attempt

Unfortunately, after much testing it was determined that this new design suffered from many flaws. These primarily being its weight and instability. Its lack of stability was a result of the parts being machined improperly and being overdesigned. As a result, we reluctantly decided to scrap this design and restore elements of the old one and modify it using components from the new design. This second design was instituted very late in development. This design was much simpler and much more stable than the initial design.

The most significant element that was retained from the initial design was the spool used for the series elastic actuator. This part maintained its position in this design, attached to the drive axle for the lower leg.

Additionally, one other element that was added after the reversion was a part that acts as a lever for the spool to pull on. This part was similar to the pi in that it was mounted to the axle of the lower leg.
However, the lower servos still couldn’t provide enough torque to lift the leg a significant distance. This was remedied by tying rubber bands between each spool and lower leg axle. This rubber band acts as another parallel elastic system. This secondary parallel elastic assists the series elastic system lift the leg by providing additional torque.
4.2 Programming and Testing

The final major phase of this project was programming and testing the robot. For this phase, we began by adjusting the angles of the upper and lower legs until the robot achieved a stable standing pose. This was followed by examining multiple gaits and weighing the benefits and disadvantages of each.

To control the servos, we used an Arbotix-M Robocontroller and programmed it using Arduino. The use of this board required the installation of hardware files and libraries provided by the distributor.
The gait we chose to test was a slow trotting gait. This meant that the pairs of legs that were diagonally across from one another would move in sync. While one pair of legs would move back the other pair would move forward.
5 Results

This project fell incredibly short of most of its goals. This was a result of many setbacks. These setbacks ranged from parts being stuck on backorder for long periods of time, old parts succumbing to wear and tear, no less than three of the boards being used to program the robot breaking, among many, many others. However, we were able to effectively implement more powerful servos and design an operational series elastic actuator. Additionally, we were able to determine a solid, standing stance for the robot and were able to program a walking cycle for the robot.

After much fine-tuning, we found that the robot could reliably stand with the upper legs at a 120 degree angle to the frame and the lower legs at a 150 degree angle to the upper legs while lowered. In this position, the upper servos were set to a position of 2048, halfway between the ends of their motion. This allowed for the servo to move 180 degrees and actuate the legs 36 degrees in either direction. The lower servos on the left side were set to a value of zero and the lower servos on the right side were set to a value of 180 for the standing position.

We were able to successfully make the left legs perform a trotting motion. Unfortunately, during the final stages of testing, the couplers on the servos on the right side of the robot snapped, rendering the right legs nonfunctional. The following explanation of the motion of the legs will be written as if all legs were functional. Before the robot begins its walking motion, the legs must be moved into position. This begins with the upper, front servos rotated 90 degrees clockwise, and the upper, rear servos rotated 90 degrees counterclockwise from their standing positions. This results in the front, left leg and rear, right leg being moved 18 degrees forward.
and the front, right leg and rear, left leg being moved 18 degrees backwards. Meanwhile, the lower, front, right and rear, left legs would be raised and the lower, front, left and rear, right legs would be lowered. The front, left and rear, right legs will be lifted off the ground. These are the starting leg positions. At this point the front, left leg and rear, right leg will begin slowly moving backwards. Once this pair of legs are halfway through this motion they have reached their standing positions and have come into contact with the ground. At this point the other pair of legs begin to move forward at twice the speed of the pair of legs moving backwards. When the forwards moving pair are at the halfway point of their trajectory, their lower legs will be lowered. When both pairs have reached the end of their motion, the lower legs on the backwards moving pair will be raised. At this point, the sequence will be repeated with the backwards moving pair now moving forward and vice versa. These sets of looping movements define the robot’s walk cycle.
Figure 11 Starting Position, Front Leg Forward and Back Leg Back

Figure 12 Front Leg Halfway Through its Backwards Motion, Just Before the Back Leg Begins Moving Forward
Figure 13 Front Leg at the End of its Backwards Motion and Back Leg at the End of its Forward Motion

Figure 14 Back Leg Halfway Through its Backwards Motion, Just Before the Front Leg Begins Moving Forward
6 Conclusion

Through this project, we continued to explore the feasibility of designing and constructing a quadrupedal robot on a relatively small budget and examined the effectiveness of series elastic systems. The end result of this project displays that, while it is certainly possible to construct a robot of this type, the deliberately small budget and subpar materials severely impacted development.

While this project was able to explore many different potential options for improving the robot, it was generally a failure. Throughout the entire process of working on this project many, many things went wrong. The sheer number, frequency, and severity of the problems experienced significantly reduced the potential this project had. Working on the project was an invaluable experience.

There are quite a few suggestions we would make for future groups. The first would be to use higher quality materials. Many of the problems experienced during testing were a result of damaged materials, such as the aluminum shafts being torn up by the sprockets. The recommendation would be to replace the control board with a different one. The type of board we used was of low quality and a total of three board had broken over the course of the project. Finally, the implementation of an IMU is still highly suggested for stability purposes.
References


Appendices

Appendix A: Arduino Code

```c
#include <ax12.h>
#include <Servo.h>

/**< Servo Name Key:
  First Letter:
  U = Upper
  L = Lower

  Second Letter:
  F = Front
  B = Back

  Third Letter:
  L = Left
  R = Right
 */

// Define lower servos
Servo LFL;
Servo LFR;
Servo LBR;
Servo LBL;

// Define upper servo IDs
int UFL = 1;
int UFR = 2;
int UBR = 3;
int UBL = 4;

int i = 0; // For loop iterator
int dir = 0; // Directional value
```
void setup() {
    // Attach servos to ports
    LFL.attach(12, 1000, 2000);
    LFR.attach(13, 1000, 2000);
    LBR.attach(14, 1000, 2000);
    LBL.attach(15, 1000, 2000);

    setPosition(UFL, 1024); // Moves corresponding leg forward
    setPosition(UFR, 1024); // Moves corresponding leg backward
    setPosition(UBR, 3072); // Moves corresponding leg forward
    setPosition(UBL, 3072); // Moves corresponding leg backward

    LFL.write(0); // Lowers corresponding leg
    LFR.write(0); // Raises corresponding leg
    LBR.write(180); // Lowers corresponding leg
    LBL.write(180); // Raises corresponding leg
}

void loop() {
    LFR.write(0); // Raises corresponding leg
    LBL.write(180); // Raises corresponding leg

    // Front left and back right step loop
    for (i = 0; i <= 2048; i++) {
        setPosition(UFL, 1024 + i);
        setPosition(UBR, 3072 - i);
        if (i > 1024) {
            if (i >= 1536) {
                LFR.write(180); // Lowers corresponding leg
                LBL.write(0); // Lowers corresponding leg
            }
        }
    
        setPosition(UBL, 3072 - ((i - 1024) * 2));
        setPosition(UFR, 1024 + ((i - 1024) * 2));
    }

delay(5); // 1/200 second delay
}
LFL.write(180); // Raises corresponding leg
LBR.write(0); // Raises corresponding leg

// Front right and back left step loop
for (i = 0; i <= 2048; i++) {
    SetPosition(UBL, 1024 + i);
    SetPosition(UFR, 3072 - i);
    if (i > 1024) {
        if (if > 1536) {
            LFL.write(0); // Lowers corresponding leg
            LBR.write(180); // Lowers corresponding leg
        }
        SetPosition(UFL, 3072 - ((i - 1024) * 2));
        SetPosition(UBR, 1024 + ((i - 1024) * 2));
    }
    delay(5); // 1/200 second delay
}
}
## Appendix B: Bill of Materials

<table>
<thead>
<tr>
<th>Item</th>
<th>Manufacturer/Distributor</th>
<th>Item #</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roller Chain Sprocket for ANSI 25 Chain, 9 Teeth, for 1/4° Shaft Diameter</td>
<td>McMaster-Carr</td>
<td>2737T1</td>
<td>4</td>
</tr>
<tr>
<td>Lightweight Sprocket for ANSI 25 Chain, 45 Teeth, for 1/2° Shaft Diameter</td>
<td>McMaster-Carr</td>
<td>60425K34</td>
<td>4</td>
</tr>
<tr>
<td>Roller Chain, Single Strand, ANSI Number 25, 1/4° Pitch</td>
<td>McMaster-Carr</td>
<td>6261K171</td>
<td>1 ft length x4</td>
</tr>
<tr>
<td>Dynamixel MX-64T</td>
<td>Robotis</td>
<td>902-0060-000</td>
<td>4</td>
</tr>
<tr>
<td>Arbotix-M Robocontroller</td>
<td>Interbotix/Trossen Robotics</td>
<td>IL-ARBOTIXM</td>
<td>1</td>
</tr>
<tr>
<td>6061 Aluminum 6 mm Diameter</td>
<td>McMaster-Carr</td>
<td>4634T32</td>
<td>9 ft</td>
</tr>
<tr>
<td>Set Screw Shaft Collar for 6 mm Diameter, Black-Oxide 1215 Carbon Steel</td>
<td>McMaster-Carr</td>
<td>57485K66</td>
<td>24</td>
</tr>
<tr>
<td>Set Screw Shaft Collar for ½ in. Diameter, Black-Oxide 1215 Carbon Steel</td>
<td>McMaster-Carr</td>
<td>9414T11</td>
<td>16</td>
</tr>
<tr>
<td>Pololu Universal Aluminum Mounting Hub for 1/4”</td>
<td>Pololu</td>
<td>1993</td>
<td>4</td>
</tr>
<tr>
<td>Actobotics Standard Hub Horns</td>
<td>ServoCity</td>
<td>525132</td>
<td>4</td>
</tr>
<tr>
<td>Savox SV-1270TG</td>
<td>Savox</td>
<td>SAVSV1270TG</td>
<td>4</td>
</tr>
</tbody>
</table>