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3-Dof leg for a quadruped robot

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Class: Intermediate Project

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Date: February 4, 2021

Abstract

The aim of this project was to develop hardware and software for a high performance robotic leg. This leg should feature 3 degrees of freedom and should be optimised for use in dynamic quadrupedal robots. To fulfill those demands, a navel, capstan based actuator, ought to be developed and used along side brushless servomotors. To perform testing and demonstrate capabilities, communication and control software should be developed and deployed. This project should also feature multiple hardware iterations, testing and performance demos.

This project was successful. All the major goals were fulfilled.

1 Introduction

Dynamic walking is at the frontier of modern robotic locomotion. It is the most advanced and difficult to achieve form of legged locomotion, due to significant periods of underactuation. Achieving this type of locomotion comes with many advantages, but it also presents significant difficulties in both mechanical and controller design.

Figure 1 – Boston Dynamics Spot mini - probably the most famous quadrupedal robot currently on the market

Utilization of such robot in industry has just began with companies like Boston Dynamics and ANYmal offering their robots in sale since the year 2020. Their are extremely expensive (they start at over 70 000USD), and see use mostly in industrial work site inspections, mapping and scanning of difficult train, military applications, search and rescue.

Advantages of dynamic quadrupedal walkers:

- ability to traverse human environments, while maintaining a small footprint,
- high agility,
- easier control than bipeds,
- ability to use point-like legs with passive stability while one leg is in the air,
- high recoverability compared to wheeled robots,
- many good examples in nature,
- familiarity and relatability for humans - because of quadrupedal pets.

In order for quadruped to see a brother utilization a significant reduction in cost is necessary. In this project I present my own attempt at developing an affordable high performance quadruped leg for dynamic walking applications

A leg is the most important and demanding part of a quadrupedal robot. The main goal of it's mechanical design should be providing the ability to exert precise ground reaction forces at any point within the accessible volume, while reaching the that point as quickly as possible. Kim et al. [2019] In order to achieve that, the mechanical design of such leg should feature the following properties:

- 3 degrees of freedom with a pointy foot
- wide range of motion
- low mass and inertia
- high torque bandwidth - ability to change directions quickly
- high accelerations
- high torque transparency - ability to measure torque exerted on the environment precisely
- backdrivable and highly efficient actuators
- mechanical stiffness

2 Related work

The MIT mini cheetah is a 9kg dynamic quadrupedal walker developed at MIT. The design of the MIT mini Cheetah leg necessitates the use of expensive manufacturing methods and materials. Mini Cheetah is inexpensive in comparison to robots like the MIT Cheetah 3, but it's still out of reach of most makers. Katz [2018] The aim of this project is to develop a leg that would be close in terms of mass and performance to the MIT mini Cheetah leg, but would be manufactureable using more accessible methods and at a BOM cost reduced at least 3 fold - from about 1500USD to about 500USD.

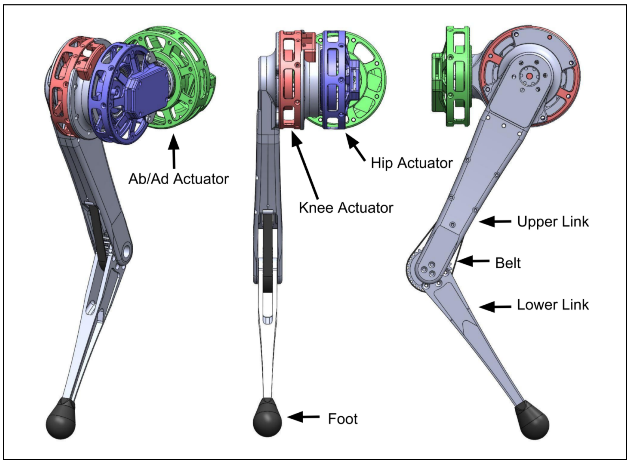

Figure 2 – MIT mini Cheetah leg CAD design Kim et al. [2019]

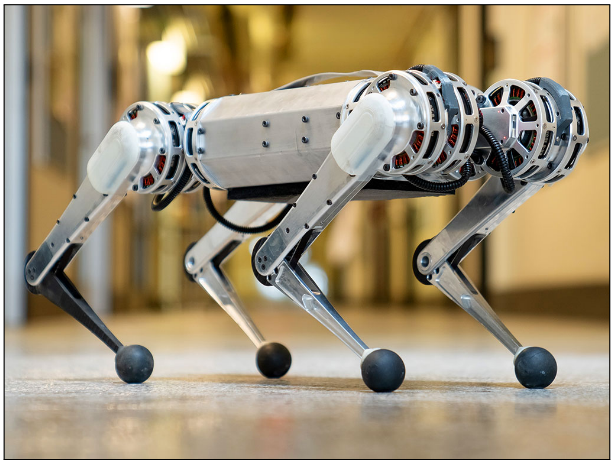

Figure 3 – The MIT mini Cheetah robot Kim et al. [2019]

3 Objective of this project

This work focuses on developing a low cost robotic leg, adapted to the demands posed by a quadrupedal dynamic walker. The objective in mechanical design is limited to a single, universal leg, that could be used as any one of the four legs of a quadruped. The objective in control software is limited to communication, inverse and forward kinematics, and a basic trajectory generator.

Goals to be achieved:

1. Write a python script for motor control via the MjBots USB to CAN-FD adapter.
2. Write a python script for forward and inverse kinematics.
3. Design and build a simplified leg with just 2 degrees of freedom to test the capstan mechanism.
4. Perform endurance testing on the 2Dof leg, improve the mechanism if needed
5. Add a third degree of freedom - the abduction/adduction joint.
6. Repeat endurance testing, this time by jumping between random positions.
7. Perform additional testing to showcase the capabilities of the developed system.

4 Utilised hardware and manufacturing methods

This project utilizes FDM 3D printing and 2D CNC routing as its main manufacturing methods. 2D routed parts can be easily and cheaply ordered in local machine shop by anyone looking to recreate this project. The motors used to power all degrees of freedom will be 8308 BLDC outrunner motors that are typically used in heavy drones. To achieve the required torque, each motor will be connected to a 1:6 capstan reducer. High resolution torque, velocity and position control will be provided by the moteus r4.3 driver which will be used for all axis. This BLDC servo controller has an integrated magnetic encoder which simplifies the build. The single leg will be controlled via the MjBots USB to CAN-FD adapter. The torque and position commands will be sent to each actuator at a rate between 150 and 200Hz.

Figure 4 – Parts 2D CNC milled out of FR4

Figure 5 – Parts 3D printed on a FDM printer

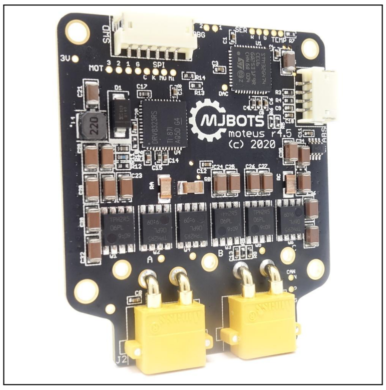

Figure 6 – The MjBots moteus r4.5 controller

Figure 7 – The 8308 90kV BLDC motor

5 Fulfilling project objectives

Described development took place over 5 months and involved 3 major hardware iterations. All 3D printed and CNC cut parts are of my design. The printer utilised is the Prusa i3 mk3s and the material used is yellow PETG from Devil Design. The FR4 parts were cut by 3DesignLab Wrocław, and the aluminum parts were cut by Blackfish studio. All FR4 parts are 4mm thick and all aluminum parts are 3mm thick.

5.1 The capstan drive

A capstan drive is a cable based reduction mechanism. It features two tangent drums connected with a cable that is wrapped around the smaller one of them multiple times. When the small drum rotates, it winds the cable on one side unwinds on the opposite side thus actuating the big drum. In this project 1:6 reduction ratios were used, with the small drum diameter of 18mm and the big drum diameter of 108mm.

Figure 8 – Capstan drives powering the hip and the knee

This type of mechanism is very cheap to produce, while featuring very good torque transparency, bandwidth and efficiency. Mazumdar et al. [2016] Hwangbo et al. [2018]

5.2 The 2Dof leg design and testing

To evaluate the capstan drive an early version of a leg with two degrees of freedom was built. Those two degrees of freedom correspond to the knee and hip joint. With this arrangement some basic jumping can be performed.

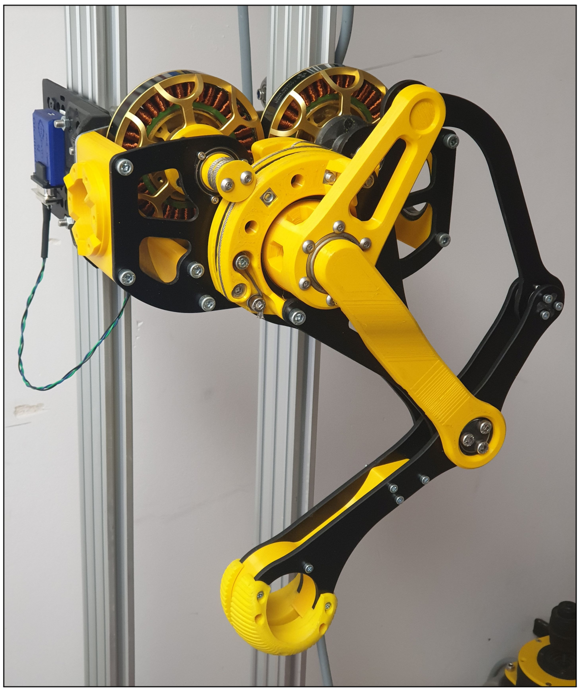

Figure 9 – First iteration of the 2Dof leg on the test stand

A test stand has been built and used for endurance testing. The leg performed continuous jumping for a period of an hour. No significant wear of the mechanism was observed, test was considered to be passed. A video demonstrating the this and some other tests like high speed trajectory execution can be watched under this link: https://youtu.be/IsvT7cYEBhE

5.3 The 3Dof leg design and testing

When the 2Dof leg was validated, the third joint called abduction/adduction could be added. Testing was still performed on a test stand. The second version of the leg was assembled, but quickly mistakes were found concerning the small capstan drum that was powering the hip. In the new higher load scenario this drum was slowly cracking under repeatable shock loads. This was fixed by modifying the geometry of this part and changing the material from PETG to PA12.

At this stage also multiple opportunities for mass reduction were found and exploited, bringing the mass of a single 3Dof leg module down to 2.7kg

With all those improvements a third iteration of the leg was built. This version underwent another endurance test. This time the jumps weren't repeatable. Every jump begun and ended in a randomly chosen spot in the accessible area. Thanks to that the mechanical properties of the assembly were tested in a closer to real life conditions. The test has been passed. Footage of the leg jumping between random positions can be seen under this link: https://www.instagram.com/p/CH3AO7jFFwN/

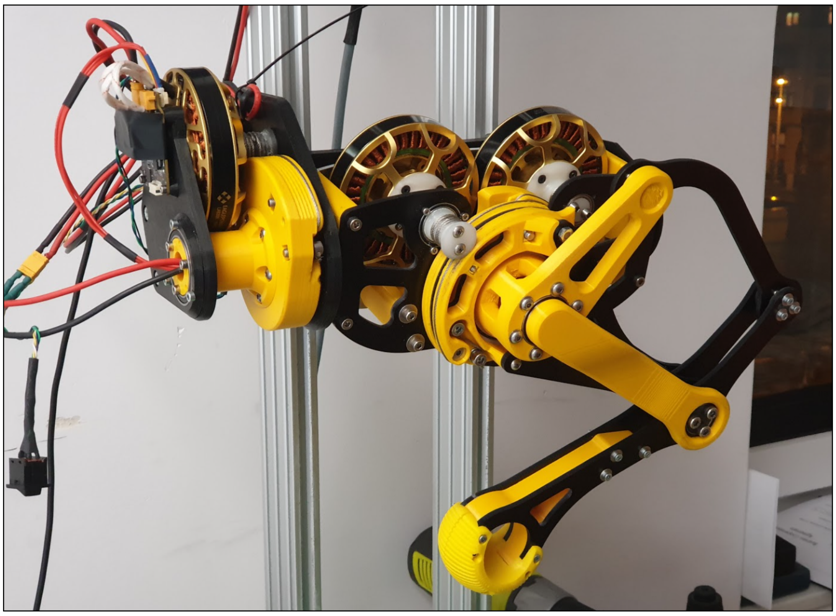

Figure 10 – Second iteration of the 3Dof leg

After completing the test some interesting demos were prepared, which included:

- bounding the position of the end of the feet inside a "virtual box",
- spiral and spherical trajectory execution,
- trot - like trajectory execution with variable stride length and direction,
- a homing sequence,
- controlling the feet position with a computer mice, which can be seen on a video under this url: https://youtu.be/p5eoATIirSU

5.4 Control software

All software for leg control was written in Python 3. Due to lack of support for python from the manufacturer of the controllers, the first step was to write a script for communication between the PC and the leg. The script that has been written exposes the following functions to the user:

```
command_stop()

set_position(position, velocity, max_torque, ff_torque,
kp_scale, kd_scale, get_data, print_data)

set_velocity(velocity, max_torque, ff_torque, kd_scale,
get_data, print_data)

set_torque(torque=0., get_data, print_data)

get_data(print_data=False)
```

Those commands provide all the basic functionality needed to controll each motor of the leg.

The next step was to solve the inverse and forward kinematics for the 3Dof leg. These solutions were packaged into Python Classes and used for almost all the demos presented before.

All that code is open source and can be found under: https://github.com/dlickindorf/moteus_canFD_serial

6 Plans for further development

Having already finished and validated a single leg, the next step will be to build an entire quadrupedal robot around it. It's name will be Stanley and it should hopefully be assembled by the end of Q1 2021.

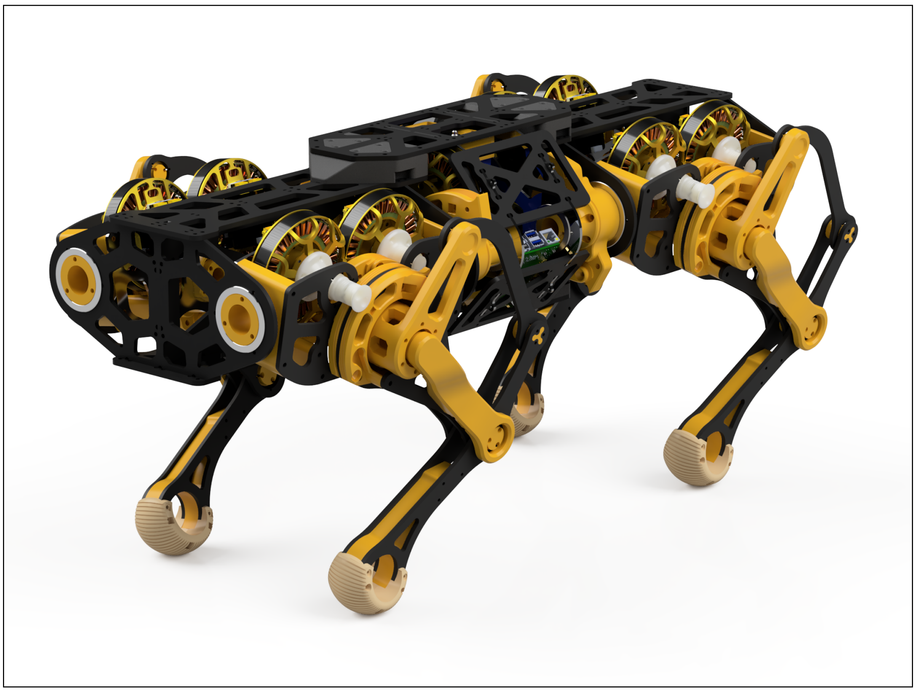

Figure 11 – Render of the Stanley quadruped robot, utilising of the 4 instances of the leg described in this project

Fruther developement of Stanley can be followe at:

https://hackaday.io/project/176726-stanley-the-capstan-based-quadruped

https://www.instagram.com/artysta_automatyk/

7 Conclusions

This project has been successful. All the goals were accomplished. It was demonstrated that thanks to capstan drives it is possible to build a highly capable leg for use in dynamic quadrupedal walkers, while utilizing accessible manufacturing methods and materials. A 3 fold reduction in cost in comparison to an estimated cost of an MIT mini cheetah leg has been achieved.

The software developed as part of this project has been open sourced and was already usefully to other roboticist around the world. An example of it's use can be found in this demonstration video by the youtuber Skyentific https://youtu.be/R2uuTfuyadk?t=652

This project will be now continued, with a final goal of building an entire quadrupedal robot named Stanley, utilising the leg developed as part of this project.

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