Thigh Actuated Bipedal Robot for Extreme Agility

Benjamin Chang
benjachang12@berkeley.edu
SID: 26452778

Jiarun Wei
sammywei@berkeley.edu
SID: 3034505085

***Abstract*— The Thigh Actuated Bipedal Robot for Extreme Agility (TABREA) is a custom built lightweight, planar bipedal robot platform for walking, running, and jumping. An auxiliary purpose for the project is to potentially serve as a hardware platform for future ME 193B/292B labs.**

I. Introduction

The TABREA project is an ongoing work-in-progress undertaken by undergraduate researchers within the Hybrid Robotics Group to create a custom lightweight planar bipedal platform in order to maximize agility and speed. Figure 1 shows a render of the biped system. Building onto this existing work, the scope of this project is to model the dynamics of the robot and explore rudimentary walking algorithms. In this project, we develop the Lagrangian dynamical model for the system, perform system identification, explore gait and controller design, and perform preliminary experiments on the hardware itself.

Fig. 1. TABREA Biped Render

II. Hardware

A. Mechanical Overview

The mechanical design of the robot takes inspiration from the MIT Cheetah Robot, utilizing key design principles for efficient legged robots to design a system capable of high performance [3]. The design features hip-mounted dual coaxial motors such that all actuators and electronics are affixed at the thigh. As a result, the knee joint is actuated remotely through a four-bar linkage through a crank/rocker configuration. The majority of the linkages themselves are manufactured out of 3D printed carbon fiber infused nylon (Markforged Onyx), which boasts strength similar to aluminum, but 25% lighter. These two factors together produce a very low inertia leg, thus reducing locomotion torque requirements and improving agility. The feet are fitted with rubber feet, effectively making TABREA a 5-link planar biped robot with point feet [1]. The CAD model in Figure 2 displays this design in detail.

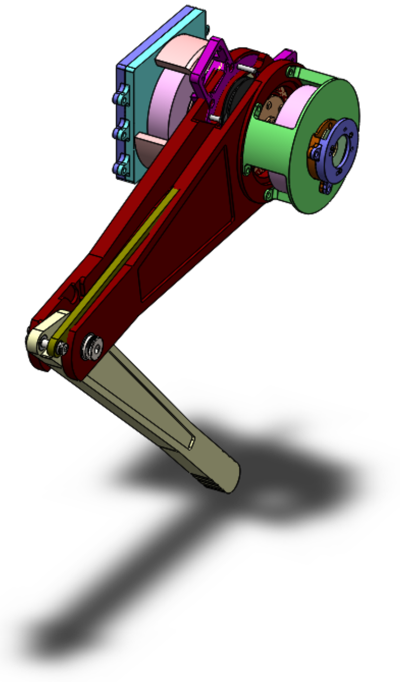

Fig. 2. CAD Model

B. Electrical Overview

Each of TABREA's legs is driven by two U8 Lite KV85 high torque density BLDC motors, each with a custom 7:1 ratio planetary gearbox. These motors are driven by Elmo Twitter Gold motor drivers and fitted with Orbis absolute serial encoders. The main processor is the Nvidia Jetson TX2, interfaced through EtherCAT. Power delivery is supplied by a DC power supply, with future plans to integrate LiPo batteries for remote operation.

III. Methods

A. Dynamics

The dynamics of the system are modeled as a 5-link walker, as presented here [2]. The generalized coordinates and planar representation are shown in Figure 3, from which the Lagrangian dynamics model with constraints are symbolically computed. Combining this model with our impact map gives us the hybrid dynamics, from which the walking controller is designed around. Although non-existent in the prototype, we assumed the existence of a hip and torso, along with their associated mass and inertia.

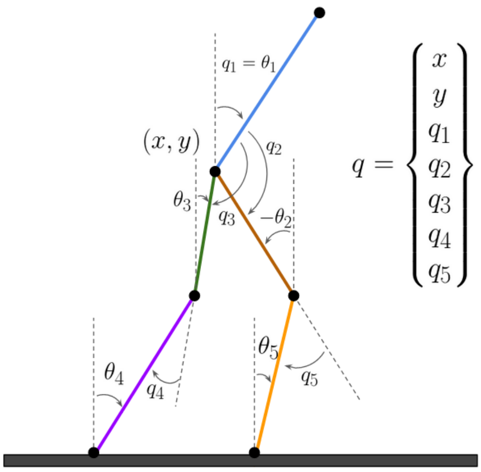

Fig. 3. 5 Link Diagram

B. Gait Design

We pick the absolute stance thigh angle, θ_3, as the crank angle that monotonically increases throughout the gait. The desired output for the other absolute angles are reparameterized in terms of this angle such that we enforce the following conditions [1].

$$L_{thigh}(\theta_2 + \theta_3) + L_{shin}(\theta_4 + \theta_5) = 0 \tag{1}$$

$$\left\| \begin{bmatrix} x \\ y \end{bmatrix} - \begin{bmatrix} x + \frac{889 \sin(q_1+q_2+q_5)}{2500} + \frac{369 \sin(q_1+q_2)}{1250} \\ y + \frac{889 \cos(q_1+q_2+q_5)}{2500} + \frac{369 \cos(q_1+q_2)}{1250} \end{bmatrix} \right\| = 0.5 \tag{2}$$

$$\left\| \begin{bmatrix} x \\ y \end{bmatrix} - \begin{pmatrix} x + \frac{889 \sin(q_1+q_3+q_4)}{2500} + \frac{369 \sin(q_1+q_3)}{1250} \\ y + \frac{889 \cos(q_1+q_3+q_4)}{2500} + \frac{369 \cos(q_1+q_3)}{1250} \end{pmatrix} \right\| = 0.5 \tag{3}$$

$$\theta_1 - \theta_1^d = 0 \tag{4}$$

Equation (1) constrains scissor-symmetry between the virtual legs that connect the hip to the stance and swing feet. Equation (2) and Equation (3) constrains the distance between the hip joint and the foot position of both left leg and right leg to be 0.5 m respectively. Equation (4) constrains the torso angle to track a desired angle. In practice the virtual constraints can be reparameterized as bezier polynomials, whose coefficients can be determined by solving a nonlinear optimization problem minimizing the integral-squared torque [2]. In addition, the 5-link robot is modeled in CAD with these gait constraints for visualization and derivation of initial conditions for the gait. The model is shown below in Figure 4.

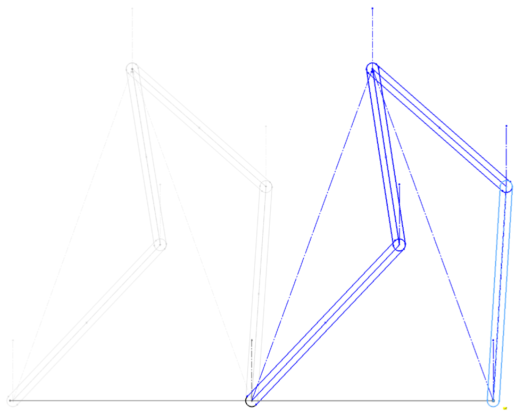

Fig. 4. CAD Model for Gait Design

C. Control

1) Challenges: The simulation of such 5 link walker poses addition difficulties compared to the 3 link walker presented in the course material. First, when two additional links are added, the complexity of the resultant Lagrangian dynamics increases exponentially, especially for the inertia matrix D. As a result, computing the inverse of D symbolically is very slow. Moreover, the computing the ground reaction force of the stance foot, F_{st}, proves to be computationally impractical, since it requires taking the inverse of the product of D^{-1} and the jacobian of the stance foot position J_{st}. Consequently, since the Lie derivatives of the system depend on F_{st}, obtaining the control law symbolically is impossible.

2) Solution: In order to solve this problem, we restructure our approach and only compute the Lagrangian dynamics symbolically. The remaining calculations are done numerically within each iteration of the numerical solver. In particular, we compute the jacobian of $L_f y$ by taking the difference of each component of $L_f y$ instead of using partial derivatives. The controller used is the I/O linearizing controller with constraints such that the stance foot stays on the ground. This exponentially cancels the output dynamics (via a simple PD controller) to enforce the gait virtual constraints.

D. System Identification

System identification of the system dynamics model parameters was carried out predominantly by measuring the

CAD file and examining the mass properties. From this model interrogation, we are able to derive the link lengths, masses, and moments of inertia to a high degree of accuracy. Several key components, like the 3D printed tibia link, were weighed using a simple kitchen scale to confirm weights, which are then used to update the densities within the CAD model. In order to achieve even greater model accuracy, additional work needs to be done to systematically update the densities of additional components, particularly fasteners and off-the-shelf components like the motor and motor driver.

IV. Results

A. Simulation

We first simulate the system by picking initial arbitrary values for the hip mass, torso length, and torso mass. By imposing the initial gait conditions as well system parameters found during system identification, we discover that the walker cannot move forward. By tuning these arbitrary parameters, we find that the torso mass is too low to give the walker a tendency to walk forward. Therefore, by increasing the torso mass and length, the walker successfully walks forward and maintains the expected gait. This offers useful design insight for future hip/torso mechanical design. Figure 5 shows a screen shot of the 5-link walker animation. (See zip file for full video of one step during the gait)

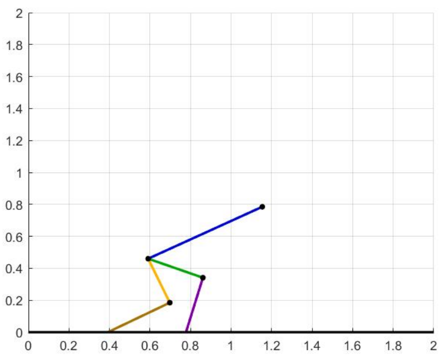

Fig. 5. Animation Screen shot

Figure 6 shows the joint motor torques over the course of one step in the gait. We observe that the motor torques peak during the beginning of the step, particularly in motor 1, which is the stance leg hip motor. The torques then monotonically decrease over the course of the gait (with the exception of motor 4, which corresponds to the stance let knee joint). This corresponds to having high energy storage at the beginning of the gait, which is then dissipated as the walker continues its step. The torques are also observed to be well under the continuous torque rating of the motors, and smooth having no jerkiness or discontinuity. For the most part, this indicates that the gait is feasible to implement on the actual system.

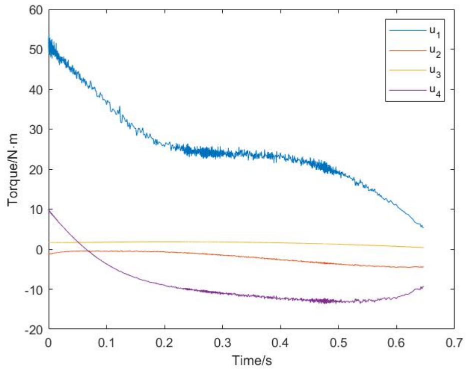

Fig. 6. Motor torque τ

The ground reaction force of the stance foot force is also reasonable, since the vertical force is much larger than horizontal force, which guarantees the foot stays within the friction cone and does not slip.

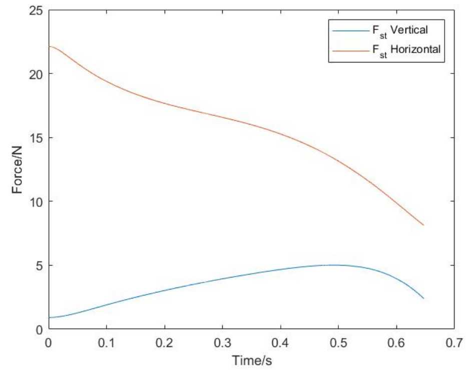

Fig. 7. Stance foot force F_{st}

B. Experiments

The current prototype TABREA system only has one leg. This, in addition to the unfinished testing gantry rig means that the hardware is not ready to test the walking controller. Therefore, for the scope of this project, we instead focus on familiarizing ourselves with the general workflow for running the control software. A simple PD torque controller function is written in Matlab to track a sinusoidal torque command for both the thigh and knee joints on TABREA. The function is converted to C code via Matlab Coder, and run on the actual hardware via Simple Open EtherCAT protocol [4]. We successfully tested a range of torque amplitudes and frequencies through bench top experiments as shown in Figure 8. Notably, the crank arm in the four-bar linkage has very visible strain during these torque tests, even when the linkages are not under load, necessitating redesign or a stiffer material in the next iteration.

V. Conclusions and Future Work

Through this project, we successfully lay the groundwork for accurately modeling TABREA's hybrid dynamics, and develop and simulate an initial algorithm for controlling a

Fig. 8. PD Torque Control Experiments

simple walking gait. The naive walking gait designed shows feasibility for TABREA's system capabilities, although it is certainly non-optimal and impractical due to scuffing. Immediate future work to continue this therefore is to develop a more optimal gait for walking by exploring the nonlinear optimization approach.

Additionally, there is quite a lot of opportunity for future work in other areas to further develop the TABREA platform. From a control standpoint, running gait and controller design can be looked into next. From a design standpoint, many aspects of the mechanical design are missing that still need to addressed. Additional work needs to be done to manufacture the second leg, design/manufacture the hip/torso links, and design/manufacture XZ gantry mount. Our experimental and simulation results demonstrated some mechanical design improvements that can be made to the next prototype iteration, such as crank arm strengthening.

REFERENCES

[1] E. R. Westervelt, J. W. Grizzle, Christine Chevallereau, Jun Ho Choi, and Benjamin Morris. *Feedback Control of Dynamic Bipedal Robot Locomotion*. CRC Press, 2007.

[2] J. W. Grizzle, C. Chevallereau and Ching-Long Shih, "HZD-based control of a five-link underactuated 3D bipedal robot," 2008 47th IEEE Conference on Decision and Control, Cancun, 2008, pp. 5206-5213.

[3] Sangok Seok, Albert Wang, Meng Yee (Michael) Chuah, Dong Jin Hyun, Jongwoo Lee, David M. Otten, Jeffrey H. Lang, *Fellow*, IEEE, and Sangbae Kim. "Design Principles for Energy-Efficient Legged Locomotion and Implementation on the MIT Cheetah Robot". *IEEE/ASME Transactions on Mechatronics, Vol. 20, No. 3*, June 2015, pp.1117-1129

[4] https://github.com/ybc82/SOEM

APPENDIX

APPENDIX A: CODE RUN INSTRUCTIONS

Change system parameters	/Codes/Initializing5link.m
Simulate, animate, and plots	/Codes/main.m