Study the dynamics of a swing motion of a Rheasus Monkey

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***Abstract*—With this project, we aim to study the dynamics of a swing motion of a Rheasus monkey [1] hanging from a bar. The swinging motion of a monkey is a complex dynamic system that can provide insights into the principles of locomotion and balance control. By replicating this motion in a robot, we can gain a better understanding of the underlying dynamics and develop new strategies for mobile robots.**

***Index Terms*—Brachiating, Swing Motion, Bio Robots**

I. Introduction

Brachiation is an form of locomotion that primates use to move from one tree branch to another by swinging their arms. This mode of movement is particularly popular among arboreal primates such as the gibbons and spider monkeys. It is the same motion which someone going to the gym performs as a form of exercise to increase their upper body strength and balance. The topic of the dynamics of brachiation has been a subject of study for physicists , who have earlier looked into the kinematics of swinging, who looked into morphology of upper limbs, and the energetics of locomotion. In this research project, we aim to analyze the dynamic system of brachiation in a rhesus monkey to gain insight into its mechanics and energetics and discuss how the study can be applied to other fields.

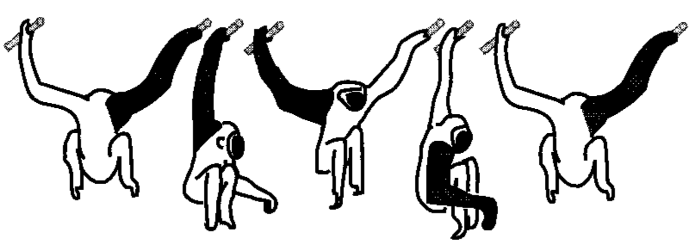

Fig. 1. Swing of a monkey

A *ricochetal* gait is a type of movement similar to running upside down. [3] The arms can be thought of analogous to the legs and the shoulder, elbow and wrist joints to the hip, knee and ankle joints. This gait also involves a touchdown phase and a flight phase that occurs between each handhold. To study movements, kinematics can be used to observe changes in the position, velocity, and acceleration of body parts over time. To create a monkey model, one could manipulate these joint angles using real-time control or by matching the joint angles and angular rates at specific points during the motion which can be calculated by first understanding the dynamics of how a monkey swings from one branch to the other and then quantifying the forces and other controls used by the monkey to maintain its balance.

Studying the swinging and hanging motion can yield valuable insights into agility and efficiency. Researchers can examine how monkeys use their bodies to navigate complex environments and adapt to changing situations, providing inspiration for developing new techniques for designing robots that can do the same.

One exciting application of brachiation research is in physical therapy and rehabilitation. Understanding how monkeys move can inform the development of exercises and therapies that improve mobility and quality of life for patients recovering from injuries or illnesses.

In addition to robotics and physical therapy, the study of brachiation has broader implications for designing equipment and tools that require precise movements, such as surgical instruments or video game controllers. By examining the mechanics of monkey's movement, researchers can develop new techniques and tools that enable humans to do the same.

Ultimately, brachiation research can help us better understand the mechanics of movement and improve our ability to navigate and interact with our environment.

II. Problem Statement

One approach to analyze brachiation is through the use of a two-link model depicting the two arms of the monkey.
Considering one arm at a time, it can be thought of as a three link structure with the links being the upper arm, the fore arm and the hand. Between these three links, there are two joints namely the elbow joint and the wrist joint. The other end of the upper arm is connected to the shoulder joint, and we consider another revolute joint connecting the hand to a fixed point, such as a roof.

To analyze the problem, we simplify the upper body linkage structure by initially considering the arm to just be one link. So, our overall model would simplify to be two link - three joint problem.
The links considered for our model are:

- Link Arm 1
- Link Arm 2

and the joints are as below:

- Wrist Joint 1
- Wrist Joint 2
- Shoulder Joint

where the two wrist joints and shoulder joint are considered to be revolute joints. In reality, there are joint limits to each of the joint, but for our analysis, we consider the revolute joints have no joint limits, which mean that they can rotate freely from 0 to 2π. Fig. 2 below shows the two link structure used for our analysis.

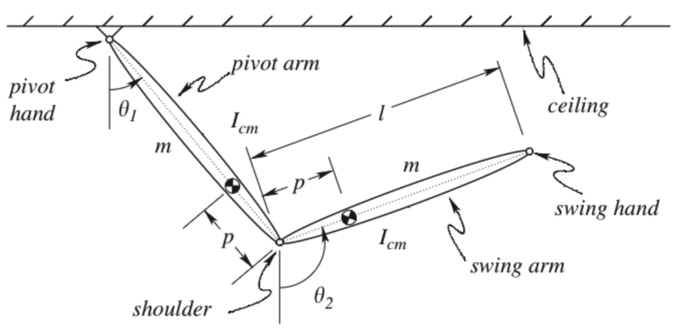

Fig. 2. Two link Monkey Model

where, θ_1 is the angle of Arm 1, and θ_2 is the angle of Arm 2 from the vertical.

We are dividing the problem into three parts:

1. We analyze and use the dynamics for a 2-link monkey model to find out the motion of the two links with respect to the ground and each other.
2. We find out the optimal trajectory which minimizes the total effort throughout one swing.
3. We use the data from the above two parts and use a simulator to visualize the trajectory.

III. Background

The brachiating monkey model has been studied extensively in the past years. For our project, we followed the work by Mario W. Gomes and Andy L. Ruina [3]. Their paper approaches modeling the monkey motion by looking for zero energy solutions and the model is developed in an iterative way starting from a single-point mass (Fig 3) model to a 5-link model (Fig 4).

Additionally, all the models described in the paper have the following properties: they are restricted to move in two dimensions, contain friction-less hinges, have no air resistance, none of the joints are springs, and plastic collisions between hand and handhold at handholds available everywhere on the ceiling.

For the purpose of our project, we focused mainly on the 2-link Monkey model (Fig 2).

The 2-link Monkey model as mentioned in Section II contains two rigid links hinged together with a joint as well as one additional joint between the wrist and the "ceiling". The torso, head, and legs are modeled as a heavy point mass located at the hinge between the two arms. This is done by adding an identical mass to both links at the hinge. This modifies the location of the center of the mass of both links moving it closer to the hinge.

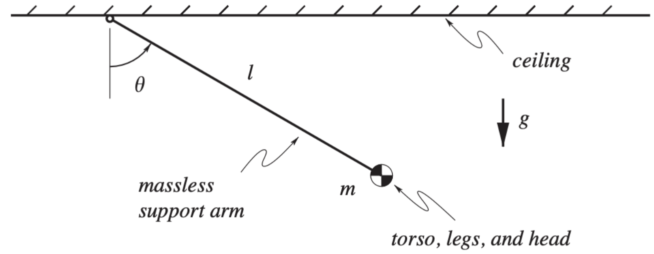

Fig. 3. Point Mass Monkey Model

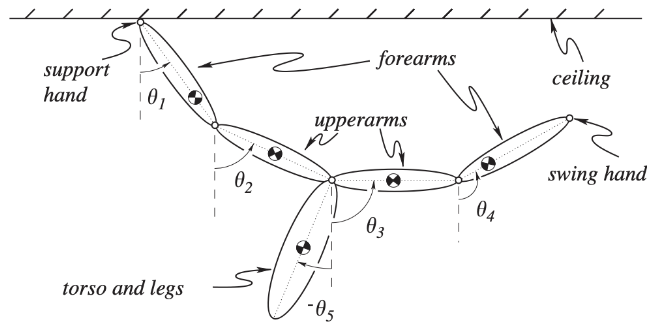

Fig. 4. Five link Monkey Model

In order to derive the system dynamics the paper defines a few things.

First, the paper describes the a swing as a continuous which starts and ends with both wrist joints on the "ceiling" and the whole system motionless. As shown in Fig 5 the monkey starts with both the wrists on the "ceiling" and throughout the motion the monkey has one wrist on the "ceiling". The motion is complete when both the wrists are on the ceiling again with a velocity of zero. The zero velocity condition has been set in order to maintain a collision-less periodic swing motion.

Next, the paper proves that the collision-less swing motion for the monkey is symmetric i.e the motion is symmetric along a vertical line going through the pivot angle. This is proven using proof by contradiction. More details about this can be found in Appendix C2 [3].

Now, using the above two conditions as well as the system information of the two-link model, the paper defines the system dynamics as,

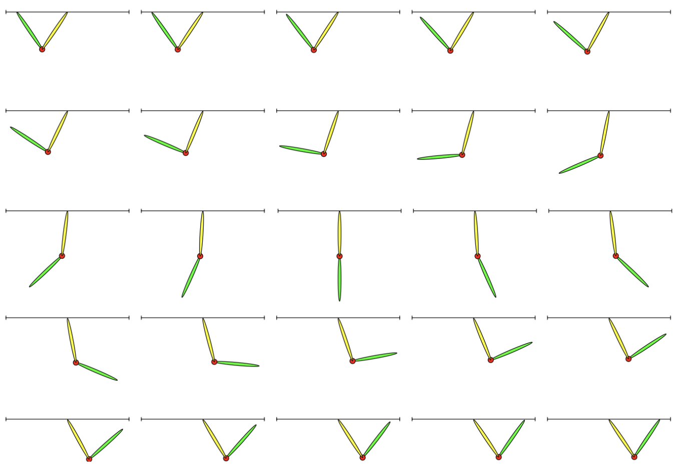

Fig. 5. Continuous Motion for 2 link Model

$$
\begin{aligned}
\ddot{\theta_1} = &- \sqrt{\frac{g}{l}} * \Big(P^2 sin(2\theta_2 - \theta_1) + P^2 \dot{\theta_1}^2 sin(2\theta_2 - 2\theta_1) \\
&+ (2P^3 + 2R^2 P)\dot{\theta_2}^2 sin(\theta_2 - \theta_1) \\
&+ (2P^3 - 3P^2 + 2PR^2 - 4R^2) sin(\theta_1)\Big) / \\
&\Big(P^2 cos(2\theta_2 - 2\theta_1) - 2R^4 \\
&+ R^2(-4P^2 + 4P - 4) - 2P^4 + 4P^3 - 3P^2\Big)
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
\ddot{\theta_2} = &\sqrt{\frac{g}{l}} * \Big(P^2 \dot{\theta_2}^2 sin(2\theta_2 - 2\theta_1) \\
&+ (2P^3 - 4P^2 + 4P + 2R^2 P)\dot{\theta_1}^2 sin(\theta_2 - \theta_1) \\
&+ (2P - P^2) sin(\theta_2 - 2\theta_1) \\
&+ (2P^3 - 3P^2 + 2P + 2R^2 P) sin(\theta_2)\Big) / \\
&\Big(P^2 cos(2\theta_2 - 2\theta_1) - 2R^4 \\
&+ R^2(-4P^2 + 4P - 4) - 2P^4 + 4P^3 - 3P^2\Big)
\end{aligned} \tag{2}
$$

where, R is the radius of gyration i.e $\sqrt{I_{cm}/ml^2}$ and P is the ratio of the center of mass of each limb with the length of the limb. Note, that since the limb has an additional weight of the torso, head, and legs modeled in, the center of mass would not be at the center of the limb, but would be closer to the joint. Additionally, the joints are unactuated in this scenario and the only force being applied on the model is gravity. We eventually did extend this model to include actuation at the joints, details of which can be found in Section IV-B.

The next sections of the report use Eqns 1 and 2 to simulate the swing motion of the brachiating monkey.

IV. Method

A. Dynamics Simulation using Solve IVP

In order to simulate our dynamics equation given by Eqns 1 and 2 we first define our system state. The state of the system consists of both the joint angles as well as the angular velocity at each joint and can be defined as,

$$x = \begin{bmatrix}\theta_1 & \theta_2 & \dot{\theta_1} & \dot{\theta_2}\end{bmatrix} \tag{3}$$

where, θ_1 and θ_2 represent the joint angles.

Now the derivative of the state or state dynamics can be given by,

$$x = \begin{bmatrix}\dot{\theta_1} & \dot{\theta_2} & F(x) & G(x)\end{bmatrix} \tag{4}$$

where, $F(x)$ is given by Eqn 1 and $G(x)$ is given by Eqn 2.

In order to get the joint angles along the entire trajectory shown in Fig 5 we use the method Solve IVP from Scipy's integrate module with an initial state value of $[0.78\ 2.4\ 0\ 0]$ which represent the monkey's initial position with both wrists on the "ceiling". The initial value is derived using the length of the limb of the monkey, more details of which can be found in Section V.

Once we have the joint angles along the entire trajectory, we use it to visualize the motion using Pybullet. (Section IV-C. Additionally, the results of the dynamics simulation are also discussed in Section V.

B. Constrained Trajectory Optimization

While simulating the dynamics equation does demonstrate how the joint angles behave over the trajectory, a more interesting problem to solve would be to compute the minimum effort or torque required to achieve the same motion for an actuated model of the system.

In order to compute that we first need to extend our system dynamics to account for actuation at each joint. The below equation give us the extended system dynamics,

$$\ddot{\theta_1} = F(x) + \tau_1 / I_{cm} \tag{5}$$

$$\ddot{\theta_2} = G(x) + \tau_2 / I_{cm} \tag{6}$$

where, x is the state vector given by Eqn 3 and $F(x), G(x)$ are the previous dynamics equations (given by Eqn 1, 2) and τ_1, τ_2 are the torque values applied at both the joints.

Now, in order to formulate our trajectory optimization problem we divide our trajectory into N equal segments. For each segment of our trajectory we would have one set of system input i.e τ_1, τ_2, one set of initial state and one set of final state (which would serve as the initial state of the next segment).

Now using these segments, we can define a vector with the states and inputs at all times. Additionally the state also has the time of the entire trajectory as a variable and can be given by,

$$
\begin{aligned}
X = [&t_f, \tau_{11} \dots, \tau_{1N}, \tau_{21} \dots, \tau_{2N}, \theta_{11} \dots, \theta_{1N}, \\
&\theta_{21} \dots, \theta_{2N}, \dot{\theta_{11}} \dots, \dot{\theta_{1N}}, \dot{\theta_{21}} \dots, \dot{\theta_{2N}}]
\end{aligned} \tag{7}
$$

Note that this vector formation has been done in order to support the Minimize function of Scipy as it minimizes the cost over a vector of all state values.

Once we have our long state vector defined, we need to define a cost function which needs to be minimized over the trajectory. Since we are minimizing over-effort we used the cost function given in [2] which is,

$$J = \int_0^{t_f} \tau^2 \, dt \tag{8}$$

Now our trajectory optimized is not a free optimization problem i.e it does have a set of constraints to it given to it by the nature of the motion and the dynamics equation. Hence, in order to enforce these constraints we first need to define them,

- The initial state of the monkey should have both its wrists on the ”ceiling” in a resting position, i.e zero angular velocity. Note, for our configuration the value of initial state was : $[0.78\ 2.4\ 0\ 0]$.
- The final state of the monkey should have both its wrists on the ”ceiling”. However the wrists should be ”flipped” i.e the angles should be symmetric about the vertical axis. For our configuration the final state was : $[-0.78\ \ -2.4\ 0\ 0]$.
- The time of the entire trajectory should be t_f.
- The final constraints on the system enforces the system dynamics on the state variables. In order to do this, we assume that the initial state and final state of any segment can be joined by a cubic spline. While this may not hold true for small N values, it holds true for large N values. Now using the system dynamics onto the initial state variable, we find the final state variables and we ”fit” a cubic spline between the two.

Now, using the minimize function of Scipy we minimize our entire trajectory using the cost function given in Eqn 8 over constraints listed in section IV-B. Section V showcases the results of this experiment in detail.

C. Pybullet Simulation

We used PyBullet to simulate and visualize the above two cases, and understand a bit more about what the angles really mean and translate to.

1) Setup: We used two rectangular bars as links where each link is 0.5 x 0.5 x 0.61 m, and one end of Arm1 is attached to a fixed ceiling named ’bar1’. The Moment of inertia for each link is calculated using the formula:

$$\begin{aligned} I_{xx} &= \frac{m}{12}(d^2+h^2) \\ I_{yy} &= \frac{m}{12}(w^2+h^2) \\ I_{zz} &= \frac{m}{12}(w^2+d^2) \\ I_{xy} &= 0 \\ I_{yz} &= 0 \\ I_{xz} &= 0 \end{aligned}$$

where, h, d, w are the height depth and width of the link.

2) Simulation: To visualize the motion of the two-link model, we utilized position control in PyBullet and used the joint angles obtained from the previous section. This allowed us to accurately represent the swinging motion of the monkey and visualize it and, thus gain a better understanding of the model’s behavior in different environments, and different test cases. Fig 6 shows the setup using the URDF written.

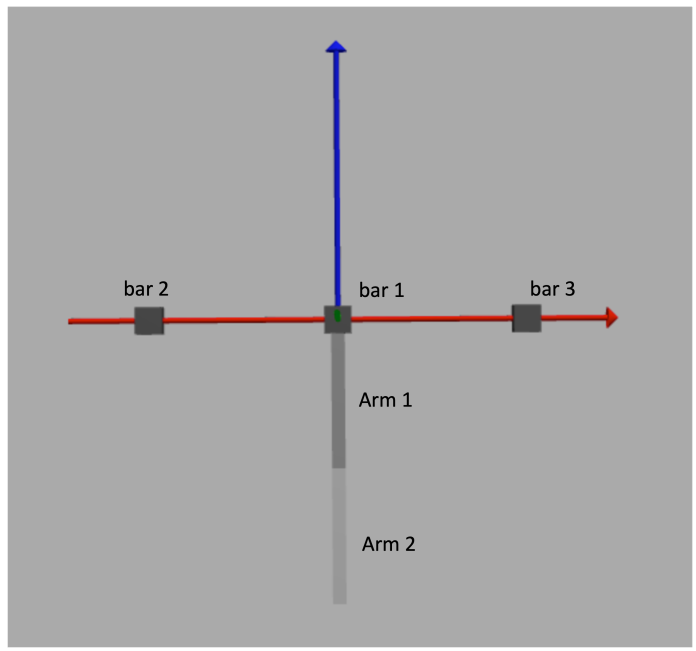

Fig. 6. PyBullet simulation setup

V. Results and Discussion

A. Two Link Simulation

By analyzing the forces and movements involved in brachiation using the two-link model, we were able to gain new insights into the mechanics of this complex movement, as detailed in the following section.

In order to simulate the two-link model for brachiation and analyze its dynamics, we used the methods outlined in Section IV. The resulting simulations using solve_ivp yielded values for the joint angles θ_1 and θ_2 in Fig 7 and Fig 8.

The initial position for the simulation is considered to be the following

$$\mathbf{x} = \begin{bmatrix} 0.78\ 2.4\ 0\ 0 \end{bmatrix}$$

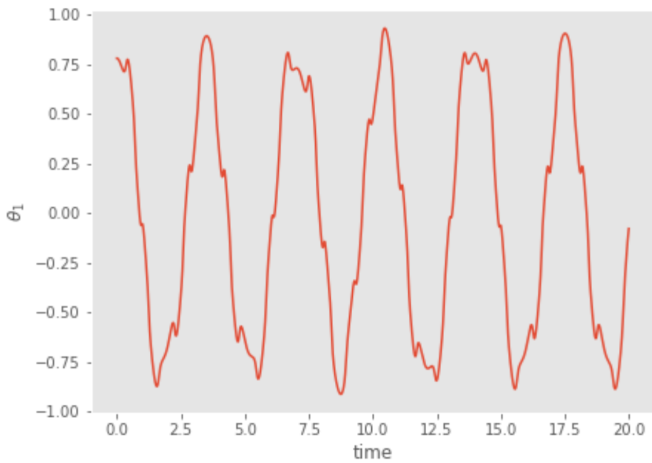

Fig. 7. Change in θ_2 with time

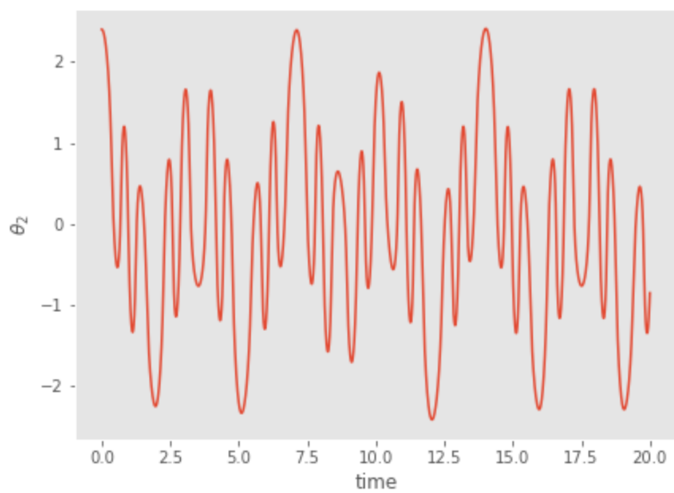

Fig. 8. Change in θ_2 with time

$$m = 3.83kg$$

$$l = 0.61m$$

$$p = 0.06376$$

$$I = 5.386 * 1e - 2$$

$$g = 9.81m/s^2$$

where m is the mass of each link, l is the length, I is the Mass moment of Inertia and g is acceleration due to gravity.

This configuration corresponds to both the arms connected to the roof, and there is no initial angular velocity applied to any of the joints. We consider one arm is let go under the force of gravity and thus, the initial condition. The solver is run for 20 seconds, and one interesting aspect of the figure is that the joint angles exhibit a periodic pattern. This periodicity is a result of the periodic nature of the swinging motion and the fact that when the arm touches the ceiling at the end, the initial and the final configuration is similar and the same dynamics can be applied again, just switching the arm in the simulation. This pattern is consistent with real-world observations of brachiation in monkeys, where the swinging motion is also periodic.

We obtained the joint angles through the solve_ivp function and then incorporated them into the PyBullet simulation to visualize the motion of the two-link model. Fig. 9 shows the trajectory of the 2-link system for one cycle of the arm leaving the ceiling, completing one turn and touches the ceiling.

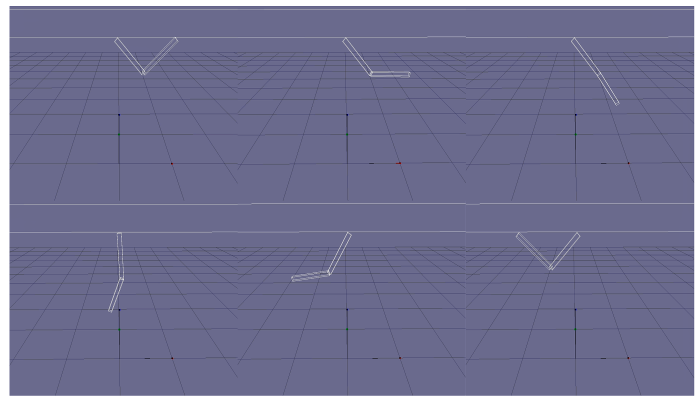

Fig. 9. PyBullet simulation for the 2-link model

Fig. 9 shows some of the intermediate points of the trajectory. The full trajectory can be found in Appendix A.

B. *Trajectory Optimzation*

We ran the trajectory optimization over the same parameters listed in Section V-A. The simulation was run for $N = 40$. The figure 10 shows the change of both the joint angles (θ_1, θ_2) with respect to time. We can see that the angles update properly and traverse from the starting position to the final position.

Similarly, figure 11 also shows the torque apploed to each joints over time. The torque values were bound between the range $(0, 20)$ however, as seen in the graph the highest torque applied was 0.6 at joint 1. This demonstrates that the model does not require a lot of torque to reach the desired final configuration.

The trajectory optimization experiment did showcase some very interesting results. It was observed that for low values of N (60) the angles have a relatively smooth plot. However if we increase the N value by a lot, even though the monkey is able to reach its final configuration, the angles do not change in a smooth fashion and we can observe a sharp change in their values (i.e jittering). This is due to the cubic spline approximation between each trajectory segment. As we increase N, the length of each segment decreases, hence at high values of N its no longer feasible to have a cubic spline approximation and a better approximation could be done by using lower order polynomials.

VI. Future Work

While the two-link model gave us a lot of insight into how the brachiating dynamics influence the motion over time, it

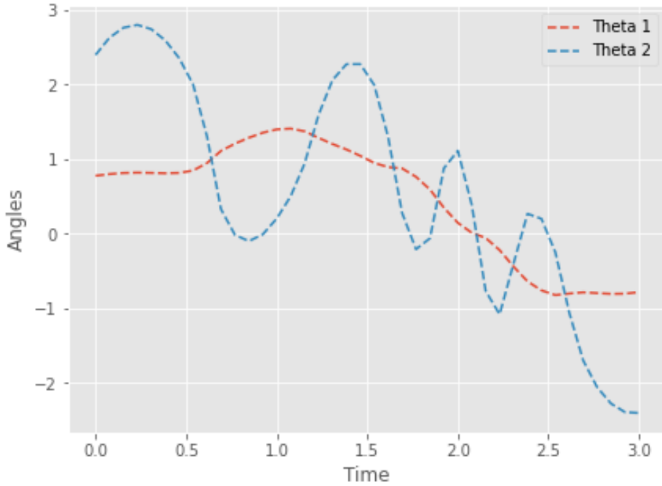

Fig. 10. Change in theta with time

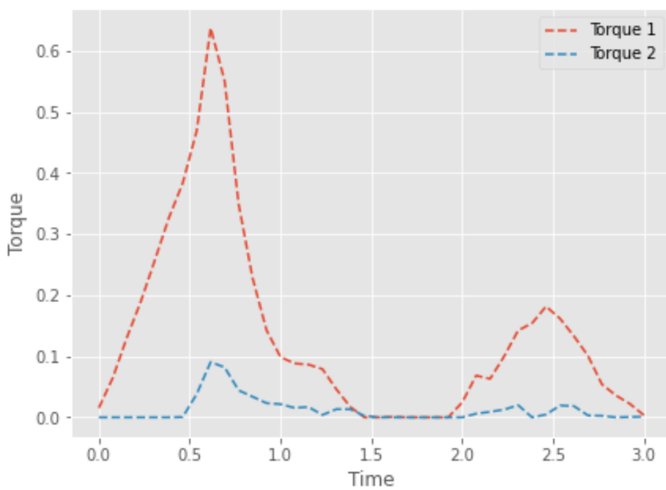

Fig. 11. Change in torque with time

would be interesting to extend this work to a 4 link model as done in [3]. This would allow us to simulate a system much closer to the actual monkey dynamics and would show us how the dynamics govern the motion of the monkey in the real environment.

VII. Acknowledgment

We would like to thank Prof. Nicholas Gravish for his constant mentorship and guidance throughout the course, especially during the project phase.

Appendix A

PyBullet Simulation Videos Link

Github Repository Link

References

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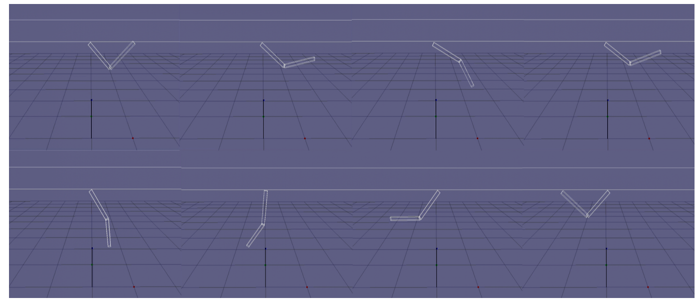

Fig. 12. PyBullet simulation for the 2-link model

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