Hexapod Robot

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***Abstract*—This report presents the design, modelling, control, simulation and analysis of an electromechanical system known as the hexapod robot using matlab simulink and solid works software. A modelling procedure is described together with analytical formulas to justify our design specifications for the hexapod robot. Tables containing these specifications can also be found within this report. The actuating device for this mechanism is the servo motor and its results are based on the analysis of the simulation values obtained in matlab. Experimental results are provided for the servo motor powered hexapod while analytical results are presented from the various force and torque calculations performed both in solid works and done by hand.**

***Index Terms*—Hexapod, Servo, Torque, Model**

I. Introduction

Group 17 was given the task of designing, modeling, simulating and analyzing an electromechanical system that includes different aspects of actuators and power electronics. Our group chose the hexapod robot as our choice for the electromechanical system. A hexapod is a robot with parallel kinematic positioning systems consisting of six independent actuator controlled struts or simply put a mechanical vehicle which walks on six legs. Hexapods offer several advantages over other types of multi-legged walking robots such as being able to maintain statically stable while in motion. A robot is considered to be statically stable when on three or more legs and due to the hexapods legs operating independently of each other it can still operate even when some of its legs become disabled. This combined with the fact that the hexapod acts on a single motion platform helps to eliminate the accumulation of guiding errors and increases precision. Furthermore it means that the hexapod can use its additional legs to gain new foot placements or control a payload. Hexapods are the fastest moving robot with the optimum number of legs for movements as adding more legs does not increase speed [1]. The Hexapod will use a servo motor as its actuating device in order to move the legs. A servo motor is a rotary actuator that allows for precise control of angular position, consisting of a motor coupled to a sensor for feedback, the feedback system increases accuracy and allows the motor to precisely control the rotary motion. Hexapods are useful for a variety of tasks particularly ones that can be dangerous for humans such as space exploration, undersea cable construction and rescue missions to name just few.

II. Design Specification

A. Problem Description

1) Design of a hexapod robot
2) Design must be statically stable
3) Must maintain dynamic stability when under pressure from a specified load
4) Modelling and simulation of hexapod robot in matlab.
5) Analysis of finished design.

B. Design Requirements

In this subsection, break the problem description down into the fundamental requirements. Your proposed design should meet each of the criteria you create.

- Robot is a hexapod therefore it should move on six legs
- In order to maintain static stability the robot should be capable of maintaining motion even when up to 3 of its legs have been disabled.
- Robot will use a servo motor as its actuating device.
- Servo motor will meet the following specifications of Table I

TABLE I
Servo Motor Specifications [2]

Frame Size	22.2 x 11.8 x 31 mm
Modulation	Analog
Torque	1.5 kg/cm
Stall Torque	1.2 kg/cm
Mass	9g
Speed	0.12 s/60 deg
Operational voltage	4-7.2 V
Rotational Range	180 deg
Motor Type	3-pole
Driver Input Voltage	DC
Pulse Cycle	20 ms
Pulse Width	500-2400 micro sec
Temperature Range	0-55 deg Celsius
Internal Resistance	0.31 Ohm
Motor Inductance	0.516 mH

III. Modeling and Simulation

A. Design Decisions

1) Motor Choice: A servo motor was chosen as it has a high rate of efficiency, allows closed loop control over the the motor allowing for very precise control with any unexpected movements being able to be accounted for. The servo is also faster, and provides more torque per size than a stepper motor does. Additionally the stepper motor produces high amount of heat when in operation which can lead to issues with the circuitry in the long run. The benefit of a stepper motor over a servo is that it does not have a limited range of movement like a servo does, however this is not a problem for us as we only need a maximum of 90 degrees of rotation from our motor leaving the servo motor as the clear choice.

2) Motors Per Leg: Three motors were chosen per leg as it allows better actuation of the leg than two. By doing this we allow the leg to essentially grab the ground and provide more grip when reaching for new locations

B. Solidworks Model

Hexapod robots have many advantages that they can leverage, these advantages include the fact that they can easily acquire and maintain their equilibrium while moving, this is known as static stability. Hexapods also have the ability to adapt to irregular surfaces and the redundancy of legs allow for greater adaptation such as the ability to continue their task even if they lose a limb. Hexapod robots are also omnidirectional and are less affected by environmental conditions than robots with wheels, [3] Thus when designing a Hexapod robot these key features should be considered.

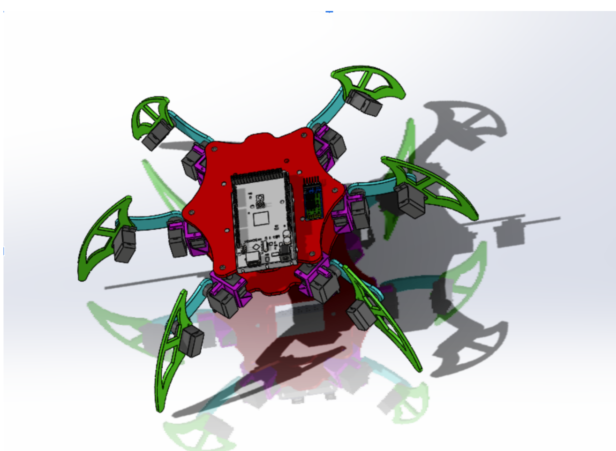

Fig. 1. Hexapod Solidworks Model

The figure 1 depicts a hexapod developed with the core concepts above in mind. This hexapod robot is developed using PVC plastic. Using this mechanical model three core concepts were pulled for future use within the simulink model. The first is the structural safety factor determined from placing the mass of a third of the robot's weight (due to 3 legs up, 3 legs down) as a pressure upon a given test leg.

Creating a model in solid works allowed us to perform simulations to determine values that would normally be difficult to calculate by hand for such an oddly shaped device. Using the solid works simulation we were able to observe the stress-strain relationship of our mechanical design. From the figure 2 it is determined that the model is structurally sound and thus is within the clear to perform test upon. Next we

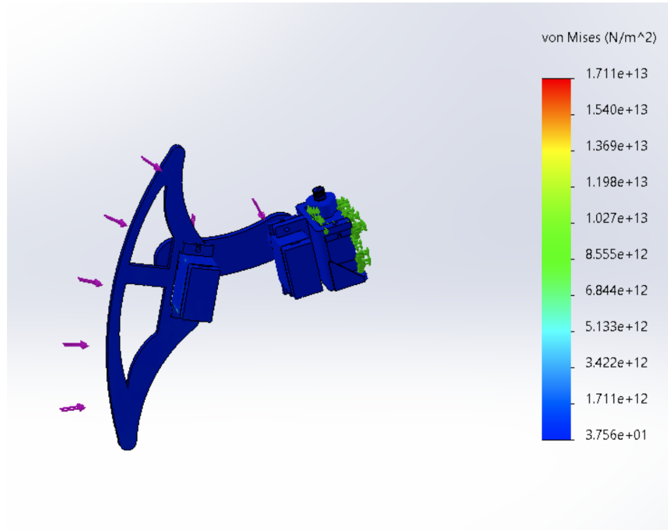

Fig. 2. Stress-Strain of Mechanical Design

move onto understanding the specifications of each link and how they interact with each other. The solids works tool was used to determine the weights and lengths of each link; these values were later recorded for future use. As well the solids work model was then used to determine the range of motion the motors would be able to achieve. While the inertias could be hand solved using the formula in the matrix.

$$I_c = \begin{bmatrix} \frac{1}{12}M_c(3R^2+H^2) & 0 & 0 \\ 0 & \frac{1}{12}M_cR^2 & 0 \\ 0 & 0 & \frac{1}{12}M_c(3R^2+H^2) \end{bmatrix}$$

It was determined that a solid works model could be used to simplify inertias within the 3 sets of components, due to the fact that the above equation assumes a perfect world model where all links are perfect geometric shapes with center of masses near the center of geometry, however it is acknowledged that this is not reality thus the above equation is best used to check the results found in figure 3 and table 2.

The following table II lists the design specifications of the solid works model

TABLE II
HEXAPOD DIMENSIONS

Foot Mass	20.18 g
Foot Length (L1)	65.5 mm
Foot Inertia (I1)	4869.88
Knee Mass (W1)	57.54 g
Knee Length (L2)	2 mm
Foot Inertia (I1)	58295.26
Thigh Mass (W3)	57.54 g
Arduino Mass (Warduino)	47 g
Half Body Length (L3)	79.72 mm
Full Body Mass (W4)	598.06 g

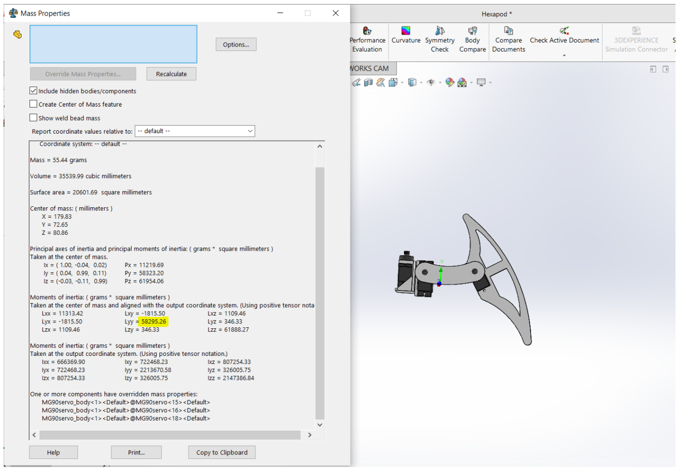

Fig. 3. Inertias and Mass of Leg Link

In order to understand the kinematic characteristics of a hexapod robot with arbitrary values imputed into link weights and link lengths we normally would use the Denavit-Hartenberg algorithm, applying it to a leg of the hexapod robot. Through the assumption that the model involved is a symmetrical structure composed of six identical legs, having three degrees of freedom in each leg we can thus assume due to symmetry that we only need to work on a single leg with a degree of freedom of 3 rather then the complete model with a degree of freedom of 18.

C. Assumptions and Equations

Before calculations for the final design could take place several assumptions regarding the forces and torques of the hexapod had to be taken into consideration. These can be seen in figures 4 and 5 along with the hexapod diagrams and variables needed for the final design.

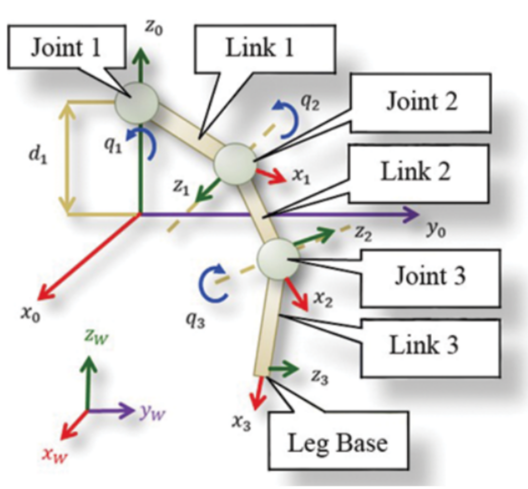

Fig. 4. Leg of Hexapod Robot
[3]

The problem of obtaining a robot's dynamic model is one of the more complex aspects in the field of robotics, and it is necessary for achieving the following objectives: design and evaluation of robot's dynamic control, sizing of actuators, evaluation of the robot's mechanical structure, and motion simulation of the robot design. [3].

Before calculating the actuation of the hexapod above assumptions need to be made regarding the torques and forces seen. These can be seen in figures 5 and 6.

Fig. 5. Topology of Hexapod

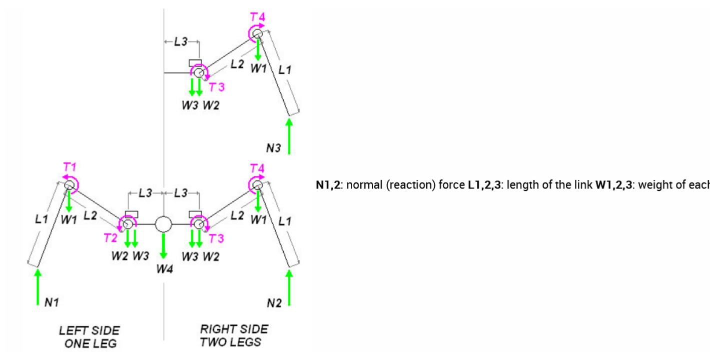

Fig. 6. Weight Distribution and Reaction Force Locations

From these figures it can be assumed that reaction forces can be equated to each other through the "3 up 3 down" system, where one side will see the reaction force split between two legs on one side and a single leg on another. From these equations we can derive the formula below relating weight of hexapod to reaction forces.[1]

$$N_1 + 2N_2 = W_4 + 6(W_1 + W_2 + W_3) \tag{1}$$

With these assumptions we can thus take this further and solve for our motor torques using these reaction forces, through the understanding at static stability the total torque at a location will be zero thus through the equation below we can solve for N2 and N3. [2]

$$\begin{aligned}\Sigma T_{LeftFoot} &= -W_1 L_1 \cos\theta_1 - W_2(L_1\cos\theta_1 + L_2\cos\theta_2) \\ &-W_3(L_1\cos\theta_1 + L_2\cos\theta_2) - W_4((L_1\cos\theta_1 + L_2\cos\theta_2 + L_3) \\ &- 2W_3(2L_3 + L_1\cos\theta_1 + L_2\cos\theta_2) \\ &- 2W_2(L_1\cos\theta_1 + L_2\cos\theta_2 + 2L_3) \\ &- 2W_1(L_1\cos\theta_1 + 2L_2\cos\theta_2 + 2L_3) \\ &+ 2N_2(2L_1\cos\theta_1 + 2L_2\cos\theta_2 + 2L_3)\end{aligned} \tag{2}$$

With N2 solved N1 we can begin solving the motor torque seen at knee location T1 and the motor torque that raises the leg T2.

$$\begin{aligned}\Sigma T_{Knee} &= T_1 - N_1(L_1\cos\theta_1) - W_2(L_2\cos\theta_2)\\ &-W_3(L_2\cos\theta_2) - W_4(L_2\cos\theta_2 + L_3) - 2W_3(L_2\cos\theta_2 + 2L_3)\\ &- 2W_2(L_2\cos\theta_2 + 2L_3) - 2W_1(L_2\cos\theta_2 + 2L_3)\\ &+ 2N_2(L_2\cos\theta_2 + 2L_3 + L_1\cos\theta_1)\end{aligned} \tag{3}$$

$$\begin{aligned}\Sigma T_{hip} &= T_2 - N_1(L_1\cos\theta_1 + L_2\cos\theta_2)\\ &+ W_1(L_2\cos\theta 2) - W_4L_3 - 2W_2L_3 - 2W_3L_3\\ &-2W1(2L_3 + L_2\cos\theta_2) + 2N_2(2L_3 + L_2\cos\theta_2 + L_1\cos\theta_1)\end{aligned} \tag{4}$$

From the “3 up 3 down” we can also build a model for the motor torque seen on a horizontal level using the figure below.

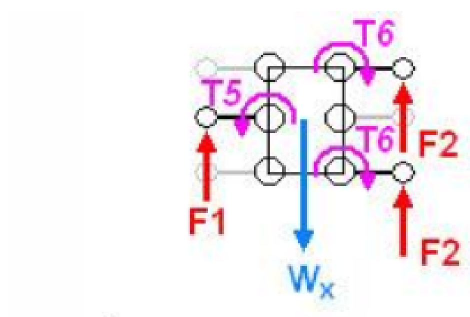

Fig. 7. Horizontal Movement Diagram

The was following assumption was made regarding the horizontal force on the hexapod using equation [5]

$$F_1 = 2F_2 \tag{5}$$

Thus allowing the equation below to be used to develop the torque seen on the motors horizontally within static equilibrium. In a perfect world simulation everything would be flat however it is noted that this hexapod would have to be able to achieve static equilibrium even when on inclined surfaces, this can be achieved through the formula below, however for our model it has been noted that sin(x) will have x equal to zero as the hexapod has been actuated in accordance with a flat surface. [1]

$$\begin{aligned}\Sigma T_5 &= T_1 - F_1(L_1\cos\theta_1 + L_2\cos\theta_2) - L_3W_x\\ &+ 2F_2(2L_3 + L_1\cos\theta_1 + L_2\cos\theta_2)\end{aligned} \tag{6}$$

The Torques Calculated using the calculations above assume that the hexapod is static stability using the “3 legs up 3 legs down” model as this is when the highest amount of torque is applied to the motors and what the hexapods actuation needs to accomplish, with a standard 25-50 percent standard of safety applied. Dynamic stability, the stability achieved only when the hexapod is in motion can be actuated using the following torque formulas. [4]

$$\tau_1 = \ddot{\theta_1}\cdot(I_1' + I_1'' + M\cdot(l_1^2 + R_3^2) + m_2\cdot(r_2^2 + r_3^2)) \tag{7}$$

$$\begin{aligned}\tau_2 = \ddot{\theta_2}\cdot(I_2' + I_2'' + Ml_2^2 + m_3r_4^2) - g(l_3cos(\theta_2+\theta_3)(3M + m_1 + \frac{3m_2}{2})\\ + l_2cos\theta_2(2M + m_1 + \frac{m_2}{2}))\end{aligned} \tag{8}$$

$$\tau_3 = \ddot{\theta_3}\cdot(I_3' + I_3'') - gl_3cos(\theta_2+\theta_3)(3M + m_1 + \frac{3m_2}{2}) \tag{9}$$

When observing the complexity of obtained expressions, it becomes evident that the greater the number of DOF a robot has, the more difficult it is to find the equations, more computer resources are consumed, and longer time and greater effort are spent trying to obtain them. As previously mentioned, an expression for the individual dynamics of a single leg of the hexapod robot is relatively easy to obtain, nevertheless the hexapod robot has six legs, that is a total of 18 DOF, therefore making the simulation more complex.

TABLE III
LEG TORQUE VALUES

Foot Torque	193.25 g/mm
Leg Torque	858.85 g/mm
Thigh Torque	Negligible

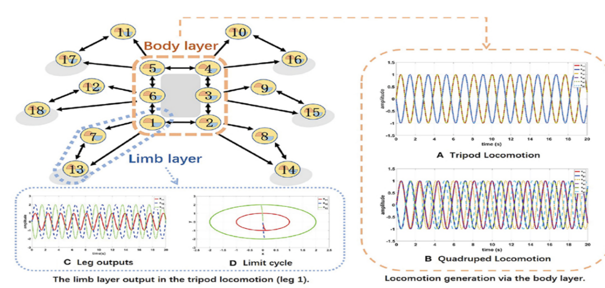

Fig. 8. Topology of Hexapods Locomotion Through Use of Torques [5]

The motor inertia was found using the formula 10 which was found in paper [6]

$$J_{motor} = \frac{J_{load}}{n^2} \tag{10}$$

The hexpods weight could be calculated as the summation of its component weights as can be seen in equation[11]

$$W_4 = W_{Frame} + W_{Battery} + W_{Elect} \tag{11}$$

The hexapods incline control was determined using the following equation [12]

$$W_x = W \sin \beta \tag{12}$$

D. Electromechanical Model in Simulink

Once the necessary calculations an physical modelling had been complete the project continued with the design of the Electromechanical model using simulink simulation software.

Before the models construction,research had first been conducted on various servo motors and their performance as well as subsequent electro mechanical models. Figures 9 and 10 represent the load effects on the system .

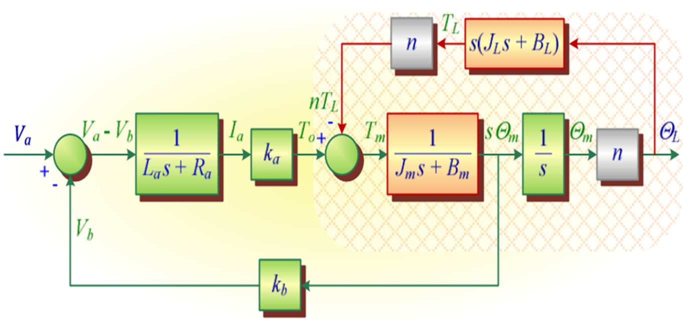

Fig. 9. Model of DC motor with external load coupled by gears

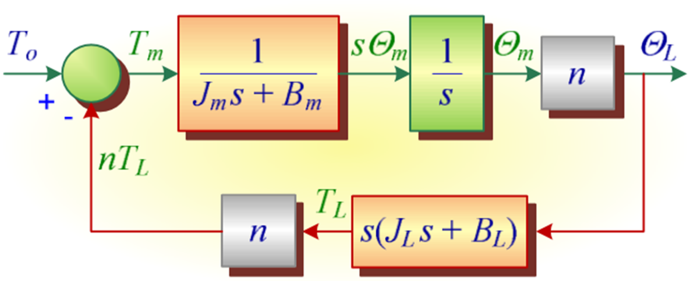

Fig. 10. Model showing load effect on motor

The figures of the the transfer function and equations used to build said transfer functions can be referred from [7]

Once the necessary research had been conducted the electromechanical model was designed as can be seen in figure 11

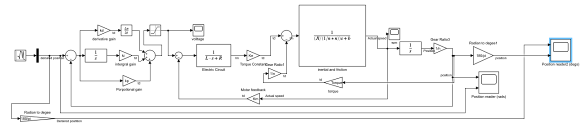

Fig. 11. Electromechanical Model of servo motor

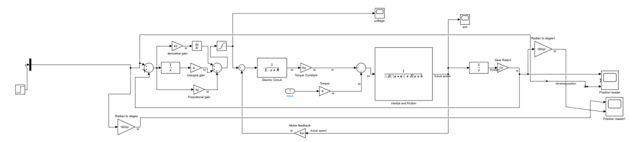

Fig. 12. Electromechanical Model of servo motor with additional torque disturbance

The model of the servo motor in figure 11 uses a PID controller to measure the difference in desired and current position adjusting the voltage output accordingly. It should be noted that the servo motor would also include a potentiometer represented by a block relating voltage to angular position and a pulse with signal, however is was assumed that the pulse with would be generated by the micro controller and their by making creation of the pulse with. The potentiometer relating the system was not necessary as both it and the controller relating voltage back to position is not necessary for a virtual simulation. During testing the PID controller and gearbox were the only variable tuned as all other variables had been calculated from data sheet and experimental with reference 9g servo model. Both the Kp and gear box were increment together as the kp decreased response time contracting the gearboxes effect on load torque, a Kd value was included to minimize overshoot. Due to the high kp value it was decided to add a saturation block to represent the motoring reaching its max input voltage saturation to allow the model to remain plausible. Based on figure 12 the group then further simplified and included a addition torque disturbance of 0.08 newtons to compensate as a factor of safety encase of environmental conditions the group then began further simulation testing. Though simulation results shown in figure 13 and figure 14 it was concluded that the created motor was able to proved a response time of 0.177 seconds for a 60 degree change and over multiple changes in position was able to average a overshoot of 3 percent each time.

IV. Conclusion and Discussion

Upon the completion of this project an understanding of electromechanical system control specifically with hexapods was developed. The design was successfully able to implement its desired functions, being able to remain statically on three or more legs and capable of withstanding any stress and strain being placed on the mechanism. The electromechanical simulation of the servo motor simulation calculated a response time of 0.177 seconds, within this time the servo rotates 60 degrees with an average overshoot of 3 Percent. The design manual however had a response time of 0.120 seconds for the servo

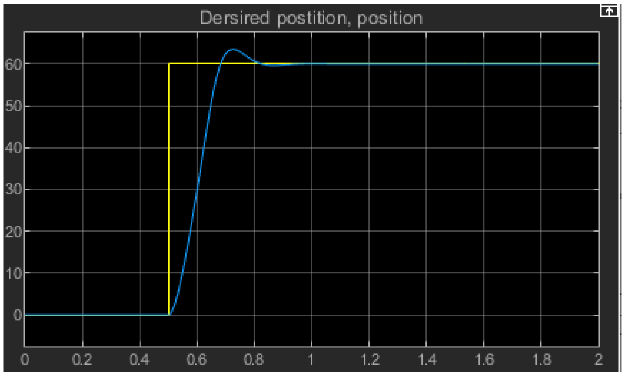

Fig. 13. Electromechanical Model Simulation Results

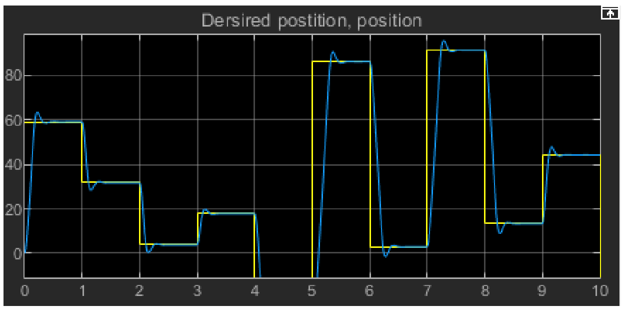

Fig. 14. Electromechanical Model Simulation varying input positions

motor, making this an area for improvement. Other potential improvements to our design included the ability to fully test our design using inverse kinematics for pinpoint positioning of the leg. Furthermore, the addition of an actuation motor and sensors to understand how incline affects the hexapod and include multiple stages as well as having the legs programmed separately in order to make it easier for the robot to walk up stairs. A final improvement would be to redesign the model so that all the legs are actuated, allowing for the hexapod to perform jumps when stuck in difficult walking situations.

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