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Exploration of an electroactive polymer actuator for application in a grasshopper inspired pneumatic robotic hopper

Christie Bielmeier

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EXPLORATION OF AN ELECTROACTIVE POLYMER ACTUATOR FOR APPLICATION IN A GRASSHOPPER INSPIRED PNEUMATIC ROBOTIC HOPPER

By
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A Thesis Submitted in Partial Fulfillment of the Requirement for the

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

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FEBRUARY 2003
EXPLORATION OF ELECTROACTIVE POLYMER FOR APPLICATION IN A GRASSHOPPER INSPIRED ROBOTIC HOPPER

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Abstract

A Hopper was created to mimic a grasshopper’s catapulting kicking action. Electroactive polymers (EAP) were investigated as actuators to simulate the grasshopper’s lightweight and strong muscles. EAPs are lightweight materials that require low voltage and yield high force with short response times. This makes them a great potential source for future micro-robotic actuators. The EAP Actuator was simulated and the potential design was studied. The development of consistent and reliable actuation electrodes and nonconductive materials was considered. In addition, the current draw of the EAP Actuator was studied, current draw prediction equations were developed, and a force output study was conducted. Finally, the EAP Actuators were compared to other conventional actuators, including pneumatic actuators, for performance and weight requirements. The EAP Actuator will ultimately be a reliable and powerful actuator for un-tethered, lightweight robotic hoppers.

The Hopper was simulated, built, and tested using pneumatic actuators. Each Hopper contained four actuators. The actuators’ contraction and release were controlled by a Parallax Basic Stamp II microcontroller and 4 relays. A 9-volt battery, a 0-20 volt variable off board power supply, and a 60 psi off-board compressed air supply were required for operation.

The Pneumatic Hopper results were compared to the EAP Hopper’s analytical results. For both the Pneumatic and EAP Hoppers, the motion was modeled in Working Model Software. These computer-generated results were compared using Lumped Mass Equations in MatLab and Two Segmented Leg Robotic Hopper Equations presented by R. M. Alexander. The Pneumatic Hopper was then tested for performance. It ultimately yielded a hop height of 2.4 mm and an average hop range of 12.7 mm.
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Introduction

Since the field of Robotics is tending toward smaller and smaller structures, the development of small high force and low power actuators is essential. Conventional actuators, such as pneumatics and motors, are will face limitations in the future because of their high power consumption and large weight constraints. Also, as wireless communication becomes more powerful, the need for un-tethered robust machines must be created. These new limitations have created the interest in development of a new field of materials and actuators.

Electroactive polymers are lightweight low voltage high force materials that have great potential as actuators. The EAP Actuators--also known as Artificial Muscles and Smart Materials--contract and release when a very low voltage (one to five volts) is applied. Currently, most studies use the EAP material in a cantilevered position and apply no or little force to the free end. Often they are used like a wiper blade. However, this paper explores the use of this material as an actuator with both ends secured. They are utilized as a linear actuator, which moves two materials by bending and drawing both ends together.

The motivation of this thesis was to design a robot that could move across the floor of a forest. This Hopper would ultimately be used in conjunction with an autonomous fire fighting robotic regime. Because of the varied and obstacle ridden nature of a forest floor, a robot that could hop over objects in its path was considered to be the most robust form of locomotion for the robot. To most effectively hop, animal hopping techniques were considered. One of the most effective jumpers is the grasshopper. It uses a catapulting method to propel itself more than 6 times its body length. The grasshopper has become the inspiration for the robotic Hopper.

This paper examines the simulation, design, and testing of a pneumatic hopper. It also studies the potential of the EAP Actuator and through simulation, explores their use in the Hopper.
Section 1  Electroactive Polymers

"Once effective EAP materials can be made, biologically inspired robots and locomotives can be made and walking, flying, hopping, digging, swimming, and diving robots would become feasible. This initiative is compatible with the recent NASA goal to develop robotic colonies”


An Electroactive Polymer is a material whose electric properties such as conductivity, charge, and shape can be controlled by an environmental change such as voltage, light, or stress. The ability to custom make these materials to fit a variety of properties such as stress, voltage, shape, and cost make them a cutting-edge material in many fields including biological, aerospace, and robotics [10]. There are several different types of Electroactive Polymers including ceramic, fluidic, and linear (see the Definitions Section for specific terminology used).

This section will cover many aspects of Electroactive Polymer Actuators such as material makeup, actuator design, and overall function. The sections include: Benefits of Electroactive Polymers Actuators, Current Electroactive Polymer Research, Nafion N-117® Ionic Polymer, Characterizing the Bending of Nafion®, and Practical Application of EAP Actuator.

1.1 Benefits of Electroactive Polymer Actuators

The Electroactive Polymer materials are often used as actuators. There are several different types for these EAP Actuators such as Ionic Polymer, Ionic Polymer Metal Composite (IPMC), Ionic Metal Polymer Composite (IMPC), and Ionic Conducting Polymer Film (ICPF). Most often the ion-exchange polymer-metal composite type of actuator is used when an electroactive polymer device is required. IMPCs are active actuators that show large deformation in the presence of low applied voltage and exhibit low impedance [24]. IPMCs
are commercially made by DuPont under the name of Nafion and then plated with platinum. The benefit of this material is that the output voltage can be calibrated for a standard size sensor and can be correlated to the applied loads or stresses [24]. The ionic polymer, human muscle, and other traditional actuator systems are compared in Table 1.

Table 1 -- Comparison of Actuator Technologies (Mallavarapu, 2001) [16].

<table>
<thead>
<tr>
<th>Actuator</th>
<th>Max. Strain (%)</th>
<th>Max. Stress (%)</th>
<th>Max. Efficiency (%)</th>
<th>Bandwidth (Hz)</th>
<th>Rel. Speed (full cycle)</th>
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<tr>
<td>Pneumatic</td>
<td>0.5</td>
<td>0.7</td>
<td>&gt;90</td>
<td>20</td>
<td>fast</td>
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<td>Hydraulic</td>
<td>0.5</td>
<td>0.7</td>
<td>&gt;80</td>
<td>4</td>
<td>fast</td>
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<tr>
<td>Piezoactuator (PZT)</td>
<td>0.2</td>
<td>110</td>
<td>&gt;90</td>
<td>5000</td>
<td>fast</td>
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<tr>
<td>PVDF</td>
<td>0.1</td>
<td>4.8</td>
<td>na</td>
<td>5000</td>
<td>fast</td>
</tr>
<tr>
<td>Shape Memory Alloy</td>
<td>&gt;5</td>
<td>&gt;200</td>
<td>&lt;10</td>
<td>3</td>
<td>slow</td>
</tr>
<tr>
<td>(SMA)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Human Muscle</td>
<td>&gt;40</td>
<td>0.35</td>
<td>&gt;35</td>
<td>10</td>
<td>medium</td>
</tr>
<tr>
<td>Ionic Polymer</td>
<td>&gt;40</td>
<td>0.3</td>
<td>&gt;30</td>
<td>10</td>
<td>slow</td>
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By examining the stress and strain values, it is shown that the actuators providing the largest displacements exhibit low stress. SMAs and Hydraulic actuators demonstrate large stress values and strain capability [16]. However, SMAs are mechanically inefficient, due to poor conservation of thermal energy into mechanical energy. Hydraulic actuators show good efficiency, but because of the weight and power requirements they are not applicable in small-scale devices [16].

The disadvantages of using the ionic polymer are that they have lower force output and lower bandwidth than compared to PZT and PVDF actuators. Due to the bandwidth limitation many applications will not be able to make use of large displacement effectively because of the limited bandwidth of the actuator. The limitation is caused by a large settling time to a step voltage, which is on the order of 5-20 seconds [16]. Currently, at Virginia Tech, research is being conducted on ways to improve the constraint[16].

In comparison to other EAPs, such as shape memory and electroactive ceramics, ionic polymers are lighter and their potential electrostriction capabilities can be as great as two orders of magnitude higher that Electroactive Ceramics, EACs, and have better response time than SMA materials [25]. Table 2 compares the three main types of EAPs.
The manufacturing of an IPMC starts with an ionic polymer that has ion exchanging capability, which is then chemically treated with an ionic salt solution of metal. It is then chemically reduced to yield polymer metal composites. The term ion exchange polymer refers to polymers designed to selectively exchange ions of a single charge (either cations or anions) with their own incipient ions. They are often manufactured from polymers that consist of fixed covalent ionic groups [24].

The bending of the electroactive polymers occurs from contraction and expansion of the outer most remote fiber (see Figure 1). The bending can be induced by electrical field [25].
1.2 Current Electroactive Polymer Actuator Research

Electroactive Polymers have received little attention until the last decade because of the difficulty in obtaining the materials and its limited actuation capability [4]. However, currently EAPs are being produced with large displacement and operate similarly to biological muscles. The polymers have low weight, great resilience, inherent vibration dampening, and abilities to withstand large actuation strains [3]. These characteristics make them very desirable for robotic actuation and in use of Smart Structures.

EAPs were first used in Aerospace systems because of their low density. In 1997, a landing balloon on the Mars Pathfinder inspired a series of inflatable EAP structures such as telescopes and radar antennas. Such projects were inspired by the development of the McKibben muscle actuators, which began in 1962. The inflatable tubes with angularly braided fiber reinforcements contract when inflated (see Figure 2). Other developments included the shape memory polymers themselves. They have the capability of “sustaining volume changes of over 40 times using pressure and heat”[3]. The field of fluids saw improvement with the development of electrorheological fluids. The EAP liquids, which exhibit an increase in viscosity under electrical field stimulation, were used in electrically controlled-hydraulic mechanisms)[3].

![Figure 2 -- McKibben Muscles [23].](image)

Currently Dr. Yoseph Bar-Cohen is leading the way for EAP materials research as Senior Research Scientist at the Jet Propulsion Laboratory. Bar-Cohen’s has a Ph. D. in Physics (1979) and M.S. in Materials Science (1973), which he received from the Hebrew University, Jerusalem, Israel. He has over 230 publications to his credit and has given hundreds presentations internationally. Much of his research focuses on the material make up of these EAPs. Some of his projects include an EAP actuated robotic arm that can win a wrestling
match against a human opponent, and interfacing signals from the brain in robotic devices. BarCohen feels that these are “an important capability for the potential of future implantation of EAP Actuators in the human body. It may become feasible in future years to control EAP actuated artificial limbs and prosthetics directly from the human brain” [2]. In addition, his projects include the development of low-mass muscle actuators.

Another leading scientist is Dr. Moshen Shahinpoor, whose work focuses on the material’s practical working application. Dr. Shahinpoor is a professor at University of New Mexico’s Mechanical Engineering Department as well as a Professor of Surgery in the School of Medicine, Neurological Surgery Department. His background includes B.Sc. degree in Chemical Engineering from Abadan Institute of Technology (1966) and M.S. and Ph.D. degrees from the University of Delaware in Mechanical (1968) and Aerospace Engineering (1970), respectively. His website displays several videos of artificial muscles performing a variety of tasks. Some simple tasks include raising and lower a bottle and bending a thin piece of EAP to use as a wiper blade. Some of the more complex systems show the controlled beating of a goat heart and skeletons riding bikes. His papers focus more on the physical and dynamical potentials and properties of EAPs.

Bar-Cohen and Shahinpoor have used IPMC films to create flexible fingers for robotic manipulation (see Figure 3). Shahinpoor has developed a miniature low-mass robotic arm that uses films of EAPs on metallic strips. The grippers consist of both two and four finger models and can lift up weight of 10.3 grams. The gripper was driven with a 5 volts square
wave at a frequency of .1 Hz [15]. Shahinpoor has also developed several apparatuses that allow the polymers to be bent. Figure 4 depicts an IMPC that is controlled by using an electric field [24].

Figure 4- Sequence of Motion of the Iono-Elastic Cantilever Beam: under a step electrical field [24].

The dynamic modeling and control of ionic polymers have been studied at the Virginia Polytechnic Institute and State University by Mallavarapu. Response time and control methods were formulated and studied. Researchers Bennett and Leo have been studying better fabrication techniques for the ionic polymers by using nickel and copper instead of precious metals such as gold and platinum [14].

1.3 Nafion N-117® Ionic Polymer

For this project Dupont’s Nafion N-117® was utilized as a base material. The Nafion N-117® membranes are non-reinforced films based on Nafion N-117® resin, which is a perfluorosulonic acid/PTFE copolymer in the acid (H⁺) form. Nafion N-117® is widely used for proton exchange membrane fuel cells and water electrolyzers. The membrane performs as a separator and solid electrolyte in a variety of electrochemical cells that require the membrane to selectively transport cations across the cell junction. The polymer is chemically resistant and durable [8].

While Nafion N-117® is conductive, it will not behave like an ionic polymer until it is plated with platinum or gold. Chemical plating or electroless plating is the most common method of preparation. “In the chemical plating method suggested by Oguro, an ion-exchange of the counter ion such as Na+ with a cationic solution (gold complex) is followed by a reduction
process in an aqueous solution of reducing agents such as sodium sulphate" [16]. This ion exchange and reduction is then repeated until desired thickness [16].

In a study at the Virginia Polytechnic Institute and State University, ionic polymers were fabricated using the chemical plating method. This is where the sample EAP material used in the paper was created. The Mallavarapu study used this method. There are two ways of depositing the platinum on the Nafion®: Sputter coating and electroless plating. Sputter coating uses gas plasma to directly deposit metallic films and is commonly used in electron microscopy. This is done in a vacuum with elevated temperatures. The membrane is dried, coated, and then hydrated. The major disadvantage of this technique is that the electrodes deposited are much more resistive after hydration [16].

*Electroless plating* is a process by which metal ions in solution are reduced to elemental form by a reducing agent directly on the surface of the part. The most common type of electroplating is the use of an electrocatalysts. In this method the Nafion is clamped between two chambers of a reactor. Platinum solution (platonic acid) is present in one chamber and a reducing agent on the other. The reducing agent penetrates through the membrane and reduces the platonic acid into the platinum metal [16].

### 1.4 Characterizing the Bending of Nafion®

Bar-Cohen and Leary, using membranes that are .2 mm X 4 mm X 20 mm, studied the bending and the tip deflection. Equation 1 was found to describe the curvature, R, of the membrane.

\[
\frac{1}{R} = \frac{PL}{EI}
\]  

(1)

where P is the concentrated load at the free end, L is the length of the cantilever beam, E is the modulus of elasticity, and I is the moment of inertia[4].

Tip Force was also measured using a five volt .05 Hz cosine wave, which resulted in a force of about .6 mN peak [4].
1.5 Practical Applications of Using Artificial Muscles

"These materials are essentially parallel-plate capacitors and will draw large peak currents when driven by a step"

-Bennett 2003[6]

There is very little published research that outlines the use of Electroactive Polymers in actual laboratory settings. While researchers Bennett, Leo, and Mallavarapu from Virginia Polytechnic Institute and State University are refining actual lab practical procedures, this field is still relatively new. Getting the EAP to actuate in a cantilevered position is quite a task in itself. Research student Bennett donated a sample of Nafion N-117 with plated platinum in de-ionized water. The best advice for handling the EAP material came in an email from him. There were two main guidelines for the effective handling of the material: hydration and preventing cations exchanging. For the material to remain effective it must stay hydrated and stored in de-ionized water. If the material becomes dehydrated, it may be rehydrated by boiling it in DI water for ½ to 1 hour [6].

The Nafon material is an ion-exchange membrane, and its performance as an actuator depends on the mobile cation inside. To prevent exchanging another cation into the material, it should not contact any solutions containing ions: tap water. The use of forceps and wearing latex gloves is recommended, as this will prevent ion exchange with the sodium in our bodies [6].

The dehydration aspect of the materials became a very important factor in designing any structure to be used in conjunction with the polymer. Any adhesive or clamping mechanisms must be able to withstand the heat of boiling for more than ½ an hour. The lightweight nature of glue and epoxies made them a good choice for securing the material. However, the glue and quickset epoxies tended to become flimsy or break when boiled. JB Weld Adhesive and EPOXI-PATCH two-part epoxy withstood the heat of boiling; however, the metallic colorant used in the epoxy resulted in several grounding issues. West System’s 105 epoxy resin and
205 epoxy hardener ultimately became the only adhesives able to be used with the EAP material.

For the actuation of the EAP material, a voltage must be applied across the thickness of the membrane by making the electrical contact with the metallic electrodes on each surface. According to Bennett, "Typically, using a clamp that has gold electrodes mounted to it has actuated the material. You may use any other metal in similar capacity, but non-noble metals will oxidize over time. Soldering wires directly to the membranes has been done with some success." In addition, he warned that the soldering iron should contact the polymer as little as possible as it dehydrates the polymer [6].

The recommended voltage for the polymer was around 1 to 3 volts for a 5 mm X 20 mm strip. More than 5 volts was not recommended for this sized strip. Above 1.23 volts, electrolysis of the water inside the materials occurs and is evident as small bubbles form on the surfaces of the sample. This accelerates the dehydration of the sample. The materials can be brushed with DI water to maintain hydration during testing. Also to prevent dehydration, if testing permits, the EAP can be actuated in a bath of DI water. Finally, Bennett suggested, "these materials are essentially parallel-plate capacitors and will draw large peak currents when driven by a step" [6].

These guidelines were very helpful in actuating the material. Soldering the wires directly to the material became impossible. The agitation of boiling the material, after the wires were

![Figure 5 -- Three Methods for Attaching Electrical Current](image-url)
secured to the materials, caused the wires to break off. As there would be two soldered connection points on each EAP actuator, this seemed like an impossible method to actuate the material. Therefore, three types of methods attaching electrical current were considered (see Figure 5).

A test stand was set up, much like Shahinpoor's, (see Figure 3), where the material was clamped between two carbon fiber pieces. Instead of gold electrodes, balls of solder were utilized. The solder ball and fiberglass clamping method could only be intermittently actuated. The material was able to be actuated using 1 to 5 volts. However, the material dehydrated very quickly and the electrolysis bubbling was visible throughout the testing. A high current was also required for actuation and this was very unreliable.

As a second attempt, soldering the wires to a small piece of metal and then clamping the EAP between the two pieces was tried. This did not work, as the EAP was very difficult to keep in place and the plates tended to slide. This was also not reliable.

Finally, the use of SPI Silver Epoxy became the best choice. The conductive epoxy was applied directly to the EAP and then the wires were laid in the epoxy and left to dry over night. This created a great contact for the actuation of the EAP with high repeatability (see Figure 6). It could be actuated with lower voltages, around 2 volts, and the connections stayed intact with repeated boiling. This also minimized the need for tabs and screws to clamp the EAP together and reduced the weight of the actuator slightly. Another benefit of using the silver epoxy was ease of repair; if the connection should break or begin to become detached a small amount of the epoxy could be utilize to secure the damaged point.

Figure 6 -- Actual Testing of EAP
It should also be noted that the bending direction of the EAP is to the side that has the positive electrode. Therefore simply changing the positive and negative wires causes the EAP to bend in the opposite direction.

In his email Bennett said that “a typical block force produced at the tip of a cantilevered sample 5mm wide and 20 mm long would be about 1 mN” [6]. A test was setup to determine the force produced by these particular EAP actuators. This setup can be seen in Section 3.5.2. For design purposes, since the EAP material used was double in size, a value of 2 mN was used.
Section 2 Robotic Hopper Construction and Design

"Only half of the earth's land mass is accessible to existing wheeled and tracked vehicles, where as a much larger fraction can be reached by animals on foot"

-Ralbert, 1986[27].

The idea of getting a robot across uneven and unpredictable terrain is not a new idea. NASA and several universities have spent many hours of research time and dollars on this subject. While legged and wheel robots dominate robotic mobility because of the less strenuous demands on the robot, several universities and researchers have turned to the animal world for design ideas. Specifically getting robots to jump or leap over objects has become an exciting idea. With the lightweight and high power potential of EAP Actuators, autonomous reliable hoppers seemed to be the best testing ground for the EAP Actuator.

In addition, a focus in robotics is on the many desirable locomotion properties that are exhibited by insects. The speed of the cockroach, the kick of the cricket, and the jump of a grasshopper are all beneficial to robotic dependability and potential. This is the foundation for using the physical dynamics of a grasshopper to propel a robot over foreign objects in its path. Because a grasshopper uses a catapulting system to achieve its jump, the weight and power within each leg must be optimized to achieve maximum jump height. This again seems to be an ideal testing ground for the EAP Actuator.

In this section, the foundation for the development and design of the Hopper are discussed: Existing Robotic Technology, The Study of Insects for Robotic Design, Dynamics and Properties of Jumping Insects, Equations of Robotic Jumping Motion, and the Grasshopper Hopping Robot Design.
2.1 Existing Robotic Technology

“If a legged system can tolerate intermittent support, then it can move all its legs to new foot hold at one time, to jump onto or over obstacles, and to use short periods of ballistic flight for increased speed. Such behavior is called running because it includes ballistic flight phase.”

--Railbert, 1992 [27]

Matauka developed the first robotic runner in 1979. His goal was to model repetitive hopping of humans. He formulated a model with a body and one mass-less leg. To simplify his model, he assumed that the duration of the support phase was short compared to ballistic flight phase, which meant that the robot stayed most of the time in flight. This also increased the stability of the robot due to less contact with the ground, which resulted in tipping [27].

Since Matauka, many studies have revolved around the idea of simple one-legged hoppers. Often legs utilized springs to absorb the downward forces and to emulate the human’s muscle absorption actions. The three main topic areas of interest are: hopping control, speed control, and posture control [27]. Within these three areas there are problems intrinsic to the flight of robots. They include: inefficiencies due to losses and negative work; need for large, high powered actuators for excitations and control of motion; excessive power remotely located; large body attitude disturbances and control effort; control complexity; vulnerabilities to damage; and impracticalities in real world environments [28].

At Massachusetts Institute of Technology from 1983-1984 Murthy built the 3D One-Leg Hopper for experiments on active balance and dynamics in legged locomotion (see Figure 7). The legs can change length and are powered by hydraulics and compressed air. The single leg made the study of balance simpler and experiments with the 3D One-Leg Hopper showed that balance could be achieved with a simple control system. It was able to hop in place, travel at a specified speed, follow simple paths, and maintain balance when disturbed. A top recorded running speed was 2.2 m/sec [17].
Also from MIT, Railbert explored running on four legs by developing the Quadruped, 1984-1988. It applied Matauka’s single leg principles to all four legs (see Figure 7). The runner was able to trot, pace, bound, and do several transitions between gaits. These gaits were diagonal legs as pairs for trotting; lateral pairs for pacing; and front pair and rear pair for bounding [17].

Another robotic hopper from MIT was Playter’s 3D Biped, which is able to pull a rickshaw carrying a grown man operating its controller (see Figure 7). This robot focused on posturing and speed [17].

Biomechanics has played a large role in many hopping robot studies. In animals, ligaments and tendons in the legs and feet stretch during each collision and store the kinetic energy. The Uniroo robot, developed by Zeglin at MIT in 1991, is modeled after the dynamics of a kangaroo (see Figure 7). It consists of a body, a three-joint (hip, knee, and ankle) articulated leg, and a single degree-of-freedom tail. Hydraulic actuators move the aluminum frame, and the springs in the ankles store elastic energy when in stance. The Uniroo demonstrated the ability to control the balance of legged robots that have a non-symmetrical mechanical structure. Regulation of angular momentum allowed the Uniroo robot to hop smoothly with forward velocities of up to 1.8m/s [17].
At Carnegie Mellon, Zeglin explored more dynamics of single legged hoppers. His Bow-Legged Hopper tries to eliminate some of the problems associated with robotic hoppers. His hopper has a leg structure of 25 cm long unidirectional fiberglass with a foot at the bottom (see Figure 8). The leg looks much like a bow and arrow because when at rest, the leg is curved providing stored energy in the elastic bending of the spring. A string is attached to limit the leg’s full extension. The bending of the bow allows for stabilization of the hopper around its center of mass [29].

Zeglin’s approach achieves a small light leg and simplified modeling of the leg. Also, the energy storage in the spring does help to minimize inefficiencies in the robot. However, the leg and hip cannot produce large torques and the leg is very vulnerable to damage. More importantly, the robot’s design only permits one control per cycled bounce and uses an off board power supply. These factors make it unpractical for real world application [29].
The Pendulum Driven Hopping Robot from the Artificial Intelligence Laboratory uses inverse pendulum dynamics to create a hopping force (see Figure 9). During walking, the robot has the ability to move in a straight line and reverse direction. The results show that such a simple but versatile robot displays stable locomotion and can be viable for practical applications on uneven terrain [21].

![Figure 10 -- 5cm Monopod hopping robot [30]](image)

In 2000 at Case Western University, Quinn and associates developed a hopping robot that could fit inside a 5 cm cube (see Figure 10). The miniaturized Smoovy motor and spherical shaped foot allows this robot to move at 1.5 body lengths per second for up to 45 minutes. This small device manages to use small amounts of power while operating autonomously [30].

![Figure 11--DARPA Hopping Robots [10]](image)

At Sandia National Laboratories, hopping research is utilized for military and space exploration. The Defense Advanced Research Projects Agency, DARPA, funded project uses a combustion-driven piston to make leaps as high as 20 feet (see Figure 11). The system uses hydrocarbon fuel instead of conventional batteries. The fuel provides a greater energy
density ratio, which makes for a longer lasting lightweight system. The grapefruit sized plastic shell rights itself after each hop positioning the piston toward the ground, but slightly askew. The hopper jumps about 3 feet in the air and 6 feet from its starting point on each jump. It can last about 4,000 hops, which is about 5 miles on a single 20-gram fuel tank. Each hopping cycle is about 5 seconds [10].

Another hopper developed by DARPA is an experimental mobile land mine platform that jumps 10 to 20 feet in the air and can go about 100 hops on a tank of fuel. The researchers are working to create self-healing minefields with hopping mines that sense an adversary’s mine clearing operations and cooperate with each other to fill in any gaps [10].

DARPA Senior Scientist Barry Spletzer says that the major benefit of hopping robots in military reconnaissance applications is that “Most mobile robots are designed to steer directly to a spot very efficiently. But over long distances, you don’t need that kind of precision. With a hopper you have time to make corrections after each jump, so it doesn’t need to steer while in air. Once we determined that semi-random mobility was okay, we knew a hopper was possible,” [10].

Spletzer’s vision for future research focuses on space exploration, “Where we want to go is Mars and the moon. With a hopper you could go much farther from the Lander. You could throw a dozen of these to search in all directions,” [10].

2.2 The Study of Insects for Robotic Design

“Animals are capable of spontaneous and non-stereotyped locomotion, such a turning, swaying, twisting, deliberately falling, jumping, climbing, and running. It therefore becomes difficult to provide joint space trajectories, in real-time for these complex movements when some limbs are simultaneously inverted and when some or all of these limbs contain abundant degrees of freedom.”

-Nelson and Quinn 1998 [19]
Insects can go anywhere, as any child that has ever put a magnifying glass to an ant knows. They are a species that is known for the fast escapes and unbelievable agility. In robotics these qualities would greatly enhance today's multi-legged robots. Several studies have been completed on the topic of insects for inspiration of robots. Ease of control of complex systems and insect inspired robotic elements are then main benefits of these studies.

Because of the complex nature of insects walking, attempts to minimize the complexity of the robot have been the springboard for many studies. Laksanacharoen minimizes the complexity of the cricket leg from 5 segments into 3 segments. In doing so, this reduces the number of degrees of freedom to three and allows for an easier analysis. He also assumes that a two dimensional movement is used in all leg activation, and an alternating tripod gait is used for walking [13]. This streamlining of variables allows for an easily controllable and programmable locomotion that is stable and has abilities that wheel robots do not.

![Figure 12- Cockroach Inspired Hexapod Robot [13]](image)

In a series of prototypes, Nelson and Quinn have developed a hexapod robot modeled after a cockroach (see Figure 12). The robot is driven by 36 double acting pneumatic cylinders, which achieve 24 degrees of freedom. A three-way solenoid valve whose position is controlled by a single turn potentiometer operates each joint. The apparatus, under a bundle of wires and hoses, is powered by 100 psi of compressed air. The tethered and high power consumption do not allow for practical use of this robot. While the robot has gone under several revisions, compressed air is a limiting factor of the apparatus [13].
Some of the complexity of insect walking has been beneficial for the study of complex neural networks and control of robotic systems. There are several types of gaits, or walking patterns that the animals exhibit. Slow walking insects have *statically stable gaits*—each leg begins to swing and immediately followed by the leg behind. Fast walking insects have *tripod gaits*—the front and back legs on each side swing in phase with the opposite side. These differences are easily controlled by a neural network. And according to Beer and Chiel, the walking can be initiated by a *flexor burst generator* (created by Pearson), which generates a pattern for walking. While the *pacemaker* dictates the speed at which the pattern is carried out, this is easily programmed and learned by neural networks. Beers says “Such simulations are carried out for two reasons: (1) they deepen our understanding of neural control behavior; (2) and they can serve as the basis for abstracting biological control principles for application in other context” [7].

The speed at which a system operates is related to the speed at which sensory information can be detected and processed. Quinn and Espenschied have studied neural networks for the distributed control of the apparatus and gait differences [22].

Another insect inspired robotic element is Muscle Wires, which are basically Shape Memory Alloy wires. These direct linear actuators utilize thin strands of nickel-titanium alloy. They can lift thousands of times their own weight. They are ideal for making small, simple insect like walking robots (see Figure 13). Muscle Wires, also known as Nitinol, have many advantages: small size, light weight, low power, high strength-to-weight ratio, precise control, AC or DC activation, long life, and direct linear action [18]. However the limiting
factor in this actuator is the long cycle time. Once the Muscle Wires are actuated it takes a long time to regain its initial position.

2.3 Dynamics and Properties of Jumping Insects

"Jumping insects use catapult mechanisms, storing elastic strain energy and then releasing it suddenly to power jump. Bennett-Clark and Lucey (1976) showed that the jumps of small insects require much higher power outputs per unit mass than any known muscle can provide. Catapult mechanisms enable work to be done relatively slowly by muscles to be released much more rapidly at take-off."

-Alexander 1995 [1]

The ability for animals to hop, jump and leap is simply related to the leg size and strength as compared to its body size. The leg bones, or exoskeletons, in conjunction with the muscles and tendons create a catapulting system to enable jumping. The more efficiently an animal can use its catapulting design, the better its jumping ability. This is why humans cannot jump as far as a kangaroo or grasshopper. This section will discuss the three most important factors of Grasshopper Jumping: Leg Design, Jump Sequence, and Spines: Jump Consistency and Control.

2.3.1 Leg Design

The main component in any hopping animal is the leg to body length ratio. Because grasshoppers are good hoppers, their two hind legs are considerably larger than the front four (see Figure 14). There are two major bones in the leg: the femur and tibia. The femur muscles, the thick part at the top of the leg, control the thinner lower part, the tibia. The foot at the end of the leg has sharp claws, which give the good traction [11].
The exoskeleton of the grasshoppers encloses the main leg muscles: the *extensor tibiae*, which cause the leg to extend, and the *flexor tibiae* muscle, which causes the leg to flex. These muscles pull on tendons, which are attached to the tibia on either side of the joint pivot, which can be seen in Figure 15. The red line depicts the tendon of the extensor muscle, while a blue line has been drawn through the tendon of the flexor muscle [11].

The lever ratio between the extensor muscle and the end of the tibia is about 1 to 35. This creates a thrust of 15 N at the end of the tibia (which is a rather larger force of 147 mN). The extensor muscle is very strong mainly because of its size and structure. In Figure 16, the extensor muscle, which is outlined in red, occupies most of the volume of the femur, while the flexor muscle, which is outlined in blue, is just a thin sheet of muscle lying along the bottom of the femur. The *pennate* structure of the muscle can also be seen in the herringbone arrangement of the muscle. This arrangement creates greater area and therefore greater strength [11].
The flexor muscle is the weaker of the two muscles. The lump, which can be seen in Figure 15, is a small black pit that resides in the femur cavity. It is critical in changing the flexor tendon angle to pull on the tibia. The lump holds the tibia flexed against the strong extensor muscle during the energy build-up. Both the extensor and flexor muscles are working through the tibia. This action creates a greater force than could be generated from the single tibia tendon’s downward push [11]. As the lump is compressed, energy is stored and the lump acts like a spring. This is how the catapulting energy is created.

“Jump height is reduced by heavy legs. However, if jump is powered by leg muscle (as in a locust) that muscle must be large to power a strong jump, and the leg cannot be very light.” In Alexander’s work on jumping robots, he compares simulations of mammal-like leg proportions with leg proportions that have reversed masses. His comparisons show “that the total mass of the leg influences jumping ability more than the distribution of the mass. This is in contrast to running, for which it is particularly important that the distal parts of the limbs should be light, to minimize the kinetic energy required for each leg swing,” [1].

2.3.2 Leg Motion During Jumping Sequence

The order in which all the muscles and tendons within the grasshopper legs function is critical to obtaining a good jump. First the Initial Flexion occurs, which is when the hind legs flex fully by contraction of the flexor muscle (see Figure 17). At the start of the jump, each leg pushes on the ground with a force of about 0.05 N, which means that the muscle must be producing a force of 10 - 15 N [11]. This is larger than the recorded force value of the EAP Actuator; therefore the constructed hopper will not produce the same magnitude of a jump as
the grasshopper (See Section 3.6.4 for Force Testing Results). For the constructed Hopper, scaling of the body’s weight and maximizing the force to weight ratio, the best jump for the Hopper is achievable for the EAP.

![Diagram of leg motion](image-url)

**Figure 17 – Leg Motion**


Second, *Co-Activation* step occurs, where the flexor and extensor muscles contract together. The contraction of the flexor muscle keeps the tibia in the fully flexed position, so contraction of the extensor muscle stresses the joint and does not cause the leg to extend. The speed of the extensor muscle contraction is slow, 2 seconds, to maximize force potential. The energy of the contraction is stored in the distortion of the cuticle springs and stretching of the extensor tendon. This mimics the energy stored in an archer's arm while bending the bow. The peak power output of each extensor muscle is about 36 mW, while the actual power lost at take-off is about 0.75 W [11].

Alexander’s jumping robot research found that “for catapult jumps with high compliances, the maximum shorting [contracting] speed on the muscle makes little difference to the height of the jump” [1]. He considers the grasshopper and locust method of jumping to be similar:

The knee extensor muscle of locust seems to be slow, with maximum shorting speeds of only 2 lengths per second. Muscles with long thick filaments can exert high stresses because large numbers of cross-bridges connect each thick filament to a neighboring thin one, but they tend to be slow because high cross-bridge cycling rates are needed to make muscle contract at any given strain rate. The long sarcomeres (strands of muscles) of the locust knee extensor muscle exert high stress, enabling a
given volume of muscle to do a large quantity of work as it shortens to deform the catapult springs. The good effect of this on the jump performance must far outweigh the small disadvantage of the muscles being slow [1].

When considering the muscle as part of a mechanical system, the type of actuator used to simulate the response of the muscle is crucial to the outcome of the hop. The speeds at which the EAP actuator contracts and releases are ideal for this type of motion.

Last, the Trigger Relaxation of Flexor occurs, which is when the leg extension is triggered by a sudden relaxation of the flexor muscle. This allows the leg to extend rapidly and forcefully, using the energy stored in the springs (Lump) [11]. The total energy required for a jump is 10 - 12 mJ.

2.3.3 Spines: Jump Consistency and Control

The feet and specifically the claws (or spines) of the grasshopper play a critical role in successful hopping. At Case Western Reserve, Dr. Laksonacharoen used video analysis to study cricket’s jumping. The cricket, which hops much like a grasshopper, requires its spines to provide traction. During the cocking and takeoff phases of the jump, the spines hold the animal in place so that the force developed by the leg extension can be translated into a lifting motion [13]. In cases where the animal lost its footing, the cricket would somersault forward or jump only a short distance. Furthermore, surgical removal of the spines resulted in a consistent and complete failure of the animal to perform a jump [13].

Laksonacharoen defines good jumping distance as a jump greater than six body lengths and poor jumps less than five body lengths. This will be the standard for this robotic hopper device.
2.4 Equations of Robotic Jumping Motion

"Catapult jumping is by far the most effective jumping technique for animals exerting insect-like ground forces. A variety of catapults have evolved in insects including the resilin springs of fleas and the apodemes and semi-lunar process of locusts. The compliances of these catapults are high enough in the locust for their elastic recoil to move the knee through its whole angular range."

-Alexander, 1995 [1]

Grasshoppers, insects, and all animals that jump have similar dynamics. Grasshoppers use a catapulting method to jump. Both universal motion equations and Alexander’s Robotic Hopper equations will be discussed in this section.

2.4.1 Universal Motion Equations for Jumping

There are several universal equations behind all jumping animals. The take-off dynamics behind all animals jumping are the same. The range, acceleration, and force are critical. The range, horizontal distance of the projectile, of any animal’s jump can be approximated by using equation 2.

\[ h_{\text{range}} = \frac{V_{\text{takeoff}}^2 \cdot \sin(2\theta)}{g} \]  

where \( h_{\text{range}} \) is the horizontal range, \( \theta \) is the take-off angle in degrees, and \( V_{\text{takeoff}} \) is the velocity at take-off while assuming air resistance is negligible [11].

For approximating the hopping range of an actual grasshopper, the take off angle is the main factor in maximizing range. It is not size or weight dependent. Therefore to maximize range,
an animal should take off at 45° from the horizontal. For an insect jumping distance of 0.75m, a take-off velocity of 2.71 m/s is required. [11].

An animal that jumps from a standing start has to accelerate its body to take-off velocity from rest. The average acceleration required to achieve a particular velocity depends on the distance, \( d \), over which acceleration takes place (see equation 3).

\[
a = \frac{V_{\text{take-off}}^2}{2d}
\]

(4)

where \( d \) is the distance over which the muscles can exert force while the feet are still in contact with the ground [11].

This equation suggests that shorter legs must accelerate much faster than tall animals to achieve the same take-off velocity. It also accounts for grasshoppers’ disproportionate leg to body length ratio.

### 2.4.2 Alexander’s Equations for Robotic Jumping

R. McNeil Alexander designed a robotic hopper that is modeled after jumping animals. For a robot with a two-segmented leg, like the grasshopper, several assumptions may be made (see Figure 18). For the purposes of equations 5 through 19, it is assumed that several muscles are fully activated instantaneously.
Vertical displacement and velocity can be seen in equations (5) and (6) and horizontal displacement and velocity can be seen in equations (7) and (8). It is assumed that each leg segment is $s$ long. The trunk has mass $m_1$, the two upper legs together have mass, $m_2$, and the two lower legs together mass, $m_3$ [1].

\begin{align}
y &= 2s \sin(\theta) \quad (5) \\
y' &= 2s \dot{\theta} \cos(\theta) \quad (6) \\
x &= s \cos(\theta) \quad (7) \\
x' &= -s \dot{\theta} \sin \theta \quad (8)
\end{align}

Assuming that the knee muscles exert moments of $T$, the legs are cylindrical rods with the center of gravity at the middle of the rod, and the leg segments are extended at $2\theta$, the energy balance of the system may be determined by the following [1]:

\begin{equation}
4T \dot{\theta} = \dot{P}_{\text{potential}} + \dot{K}_{\text{kinetic}} 
\end{equation}

where $\dot{K}$, $\dot{P}$ and $T$ are the following:

\begin{align}
\dot{K} &= \frac{\dot{y}^2}{12} [m_6 + m_4 \tan^2 \theta] + \frac{\dot{y}^2}{24} [m_4 \dot{\theta} \tan^2 \theta \sec^2 \theta] \\
\dot{P} &= \frac{gym_4}{4} \\
T &= F_{\text{actuator}} s 
\end{align}

It then can be expressed, after much algebraic manipulation, that the take-off motion is the following:

\begin{equation}
y = \frac{48T \sec \theta - 6m_5gs - m_4 \dot{y}^2 \tan \theta \sec^3 \theta}{2s(m_6 + m_4 \tan^2 \theta)} 
\end{equation}

where $m_4 = m_2 + m_3$ \quad (14)

\begin{align}
m_5 &= 4m_1 + 3m_2 + m_3 
\end{align}
\[ m_6 = 12m_1 + 7m_2 + m_3 \]  \hspace{1cm} (16)

\[ m_{\text{total}} = m_1 + m_2 + m_3 \]  \hspace{1cm} (17)

The force required to accelerate the vertical components is:

\[ F_{\text{ground}} = m_{\text{total}} g + \frac{1}{4} m_2 \ddot{y} \]  \hspace{1cm} (18)

According to Alexander, “As a general rule, larger animals exert forces that are smaller multiples of body weight; human’s standing jumps exert forces on the ground of 2-3 times body weight; and fleas over 100 times body weight. However, frogs exert maximum forces only about 3.5 time body weight despite the difference in size between them and humans, the maximum forces they exert are not much greater relative to body weight,” [1].

A hop can be considered when the ground force is equal to 0 or when \( y = 2 \times s \) and it can be assumed that \( \dot{y} = \dot{y}_{\text{off}} \) and \( y = y_{\text{off}} \). Finally, the hop height at the center of mass for the entire body can be determined by the following:

\[ H_{\text{height}} = \frac{m_2 \dot{y}_{\text{off}}^2}{32 m_{\text{total}}^2 g} \]  \hspace{1cm} (19)

where \( Y_{\text{off}} \) is equal to the initial vertical displacement [1].

Using equation 19 and considering that the mass center is in the base component of the Hopper, the jump height of the Hopper can be measured.
Section 3 The Grasshopper Hopping Robot Design and Potential with Use of the EAP Actuator

To optimize the jumping ability of a Robotic Hopper, a lightweight and low power chassis was considered. Heitler's illustration of a grasshopper kicking was best suited for these conditions (see Figure 17 and Section 2.3.2). The Hopper was built according to the illustration, but the EAP Actuators replaced the red and blue muscles shown. Also, a spring was utilized for the yellow lump muscle. The overall shape was created and put into Working Model to find the best actuator and spring orientation.

This Hopper was originally designed to demonstrate the abilities of the EAP Actuators. For a sample EAP Actuator 5 mm wide and 20 mm long, a typical block force produced at the tip would be approximately 1 mN [6]. This small actuator force was a critical factor in design of the Hopper. This factor reduced the overall size of the body and legs for the Hopper. In addition, it dictated the use of a fiberglass chassis to minimize weight and a streamlining of all components. The legs and body were less than four inches cubed and weighed only 3.65 grams when completed. This very low weight was ultimately achieved by using the fiberglass design.

The Hopper was designed to meet the criteria of the EAP Actuator. However, the EAP Actuators were not implemented. There were several issues with hydration and connection of the EAP material to the Hopper (see Section 3.6 for a Design Related Issues). This design was then tested using pneumatic linear actuators. This section explores the potential for the EAP Actuator with use in the Hopper. All calculations and simulations are considered for the EAP Hopper. This section shows the design results of the EAP Hopper: The Grasshopper Inspired Hopper's Components, Working Model Software Design Results for the EAP Hopper; Working Model and Lumped Mass Equations Design Comparison for the EAP Hopper; Alexander's Equations for Design of the EAP Hopper; Results of Design Analysis, EAP Actuator Design Issues, and EAP Hopper Design with EAP Actuator Best Orientation.
3.1 The Grasshopper Inspired Hopper’s Components

There were several initial requirements for the Hopper. The need for it to have low mass and durability suggested the use of composite materials. Because of their availability and high strength to weight ratio, the body and leg designs were made of fiberglass (see Figure 19). The fiberglass weave was used with a 2 to 1 ratio of the West System 105 Epoxy resin to 206 Slow Hardener. The ¼” thick body was made from a hand lay-up 45 degree angled fiberglass weave. Both the body and upper and lower legs were machined and cut to size. See drawings for body and leg design in Appendix B.

Figure 19 – Hand Lay-Up Woven Fiber

Because of weight and machining limitations, the body of the Hopper was designed to be about an inch and a half by two inches and have legs that are an inch and a half tall. For actual size and dimensions of the Hopper’s Leg and Body see Appendix B. For ease of fabrication, metal wire was used for the front legs. This minimized the need for braces and screws, which would be required if fiberglass was used for each leg. See Table 3 for weights of the Hopper built.

Table 3 – Built Hopper Component Weights

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight (grams)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of base</td>
<td>.79</td>
</tr>
<tr>
<td>Mass of upper leg</td>
<td>.72</td>
</tr>
<tr>
<td>Mass of lower leg</td>
<td>.66</td>
</tr>
<tr>
<td>Total Mass (with front legs)</td>
<td>3.65</td>
</tr>
</tbody>
</table>
To manipulate the Hopper, a Parallax Basic Stamp II, BSII, microcontroller was used (see Figure 20). The PIC16C57 surface mount is the single most popular BASIC Stamp module. The BSII is widely used in educational, hobby, and industrial applications. It is able to handle 4,000 instructions per second with its 20 MHz speed. The 16-pin chip uses a serial PC interface for downloading programs and provides enhanced debug features [20]. For a complete wiring schematic of the chip see Appendix B.

![Figure 20 -- Basic Stamp II Microcontroller [20]](image)

For the purposes of the Hopper, the Stamp pins activated a relay and then a power supply voltage was applied across the EAP. The Stamp pins output 5 volts, but do not have enough current to effectively activate the EAP. At 5 volts, the pins put out 14 mA of current and over 300 mA is required for EAP activation. Therefore a relay was necessary.

Finding a relay that would operate with the low voltage (around 1 volt) that the Stamp outputs was difficult. An ELK Products Inc. Sensitive Relay DPDT with 1.2mA trigger was required (see Figure 21). The operative voltage is 12 or 24 volts and draws 60mA current and has a trigger voltage of 4-24 VDC [9]. The wiring diagram for the relay can be seen in Figure 22.

![Figure 21- ELK Products Inc. Sensitive Relay [9]](image)
Using the Sensitive Relay allowed for simple programming and minimal wiring. For complete wiring diagram and integration with the Basic Stamp II Microcontroller see Appendix B.

To check the operation of the relay and stamp interface with the EAP Actuator, the cantilevered EAP Actuator was attached to the relay and tested. The EAP Actuator was activated for 5 seconds and then released. The EAP Actuator responded consistently as the switch on the relay was activated. No data was taken from this setup (see Appendix B for wiring diagram).

3.2 Working Model Software Design Results for the EAP Hopper

To best design the Hopper using EAP Actuators, Working Model was used to mimic the kicking action of the legs (see Figure 23). The two-dimensional model utilized actual weights and materials for the Hopper built (see Table 3). Two linear actuators simulated the pulling of the electroactive polymers. In addition, a spring slot orientation was used to model the catapulting aspect of the jump. The dimensions of the model were created from the Heitler
kicking design (see Section 2.3.2 and Figure 17). The legs were scaled to an over all size that could be machined in the RIT machine shop and was in proportion to the picture's design. The exact placement of all apparatuses was found after a repeated number of orientations (for exact hole and component location see Appendix B). The orientation that optimized the downward speed of the kick is seen in Figure 23.

![Diagram of kicking leg](image)

**Figure 23 -- Working Model Software Representation of the Kicking Leg**

After using several different actuator setups and measuring the lower leg's maximum velocity, the most effective setup was determined. The best orientation was when the extensor muscles pulled at a 2 mN force, the flexor muscle pulled at a 2 mN force, and the spring constant was 3 N/m. The flexor muscle became the dominant force in the setup. It required a force of 2 mN to overcome the weight of the lower leg. The positioning of the connection point of the actuators on the lower leg became critical in determining the best kick.

Also through varying other parameters, it was found that the extensor muscle’s strength was not as critical to kick speed. As long as the spring was compressed, the muscle could have as
little force as 1mN. The force did not affect the speed at which the leg kicked. The speed relied on the spring compression. Figure 24 shows the velocities of each muscle.

![Figure 24 - Lower Leg Velocity Using Working Model](image)

The Working Model setup yielded values of speed and acceleration. The average values for the upswing and the kick can be found in Table 4. The acceleration varied considerably throughout the kick portion of the model because of the spring and actuator working together.

| Table 4-- Working Model Lower Leg Properties Table for the EAP Hopper |
|-----------------------------------------------|------------------|
| Peak velocity                              | 42.729 m/s       |
| Average Velocity of Lower leg on upswing    | 5.719 m/s        |
| Average Velocity of kick                    | 12.349 m/s       |
| Average Acceleration of Lower leg on upswing| 12.045 m/s²      |
| Average Acceleration of kick                | 156.065 m/s²     |
| Peak acceleration                           | 13650 m/s²       |

When the lower leg was perpendicular to the ground, the EAP Hopper was assumed to jump. These results of acceleration are found in Table 5. Both Tables 4 and 5 will be compared to the Lumped Sum Approximation found in Section 3.3.
Table 5 – EAP Hopper Working Model Results for Lower Leg the Instant Before Hop

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity vertical direction</td>
<td>Vx</td>
<td>.206</td>
<td>m/s</td>
</tr>
<tr>
<td>Velocity horizontal direction</td>
<td>Vy</td>
<td>.067</td>
<td>m/s</td>
</tr>
<tr>
<td>Velocity</td>
<td></td>
<td>.217</td>
<td>m/s</td>
</tr>
<tr>
<td>Angular velocity</td>
<td>Vϕ</td>
<td>9.404</td>
<td>rad/s</td>
</tr>
<tr>
<td>Acceleration vertical direction</td>
<td>Ax</td>
<td>.254</td>
<td>m/s²</td>
</tr>
<tr>
<td>Acceleration horizontal direction</td>
<td>Ay</td>
<td>.123</td>
<td>m/s²</td>
</tr>
<tr>
<td>Average Acceleration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angular Acceleration</td>
<td>Aϕ</td>
<td>184.365</td>
<td>rad/s²</td>
</tr>
</tbody>
</table>

3.3 Working Model and Lumped Mass Equations Design Comparison for the EAP Hopper

To check the feasibility of the Working Model Results, free body diagrams of the leg orientation were created and put into MatLab Software. The numeric results for MatLab and working model were then compared. The model used is an approximation of the actual model (see Appendix D). This should be used as a working model approximation only.

To evaluate the Working Model Results effectively, a Lumped Mass Model was created for distinct points in time (see Figures 25, 29, and 33). The first “drawback” phase was considered from time 0 to .13 seconds. This is where the flexor muscle contracts the lower leg. The second phase, the cocking phase, occurs from .13 to .15 seconds. This phase shows the spring compression using both muscles. Finally, the third phase, the kicking phase, is from .15 to .268 seconds. In this phase the flexor muscle is released while the extensor muscle remain compressed, which causes the kicking motion. These time values were created in the best Working Model setup.

Looking at Figure 25, forces F1 and F2 were initially considered to be constant forces that acted perpendicular to the rotating leg for all time. This did not yield good results. To best model the system, the forces were considered acting through a fixed point. Therefore, both endpoint positions of the forces do not change as the angular position of phi does (see Figure
25). Thus alpha1 and alpha2 are the angular positions of the forces F1 and F2 as measured from the horizontal (for the extensor muscle and flexor muscle forces) and are related to phi. For Phase One F2 is zero.

Figure 25 -- Phase One Free Body Diagrams
Left to right: Alpha Greater Than Phi and Alpha Less Than Phi

For the Phase One angle α1 was found using the following diagram, Figure 26. Using this configuration, equation 18 was found.

Figure 26- Lumped Mass Phase 1 for Alpha1
\[
\alpha_1 = \tan^{-1}\left(\frac{L_2 \cos \phi + L_1 \sin \phi - L_3}{L_4 - L_2 \sin \phi + L_1 \cos \phi}\right) \tag{20}
\]

The system equations for Phase One were derived from the model shown in Figure 25. For the equations of motion for \( \alpha_1 \) less than \( \phi \) see equations 19 and 20.

\[
I \ddot{\phi} = wl \sin \phi - F_1 \sin(\alpha_1 - \phi)L_2 - F_1 \cos(\alpha_1 - \phi)L_1 \tag{21}
\]

\[
m \ddot{X} = -kX + F_1 \cos \alpha_1 \tag{22}
\]

Using these system equations a Simulink model was created in MatLab to find the angular position, \( \phi \), and the \( x \) displacement from equilibrium (see Appendix A). For equations of \( \alpha_1 \) greater than \( \phi \), equation 21 becomes equation 23 and equation 20 is still valid.

\[
I \ddot{\phi} = wl \sin \phi - F_1 \sin(\phi - \alpha_1)L_2 - F_1 \cos(\alpha_1 - \phi)L_1 \tag{23}
\]

Using these system equations a Simulink model was created in MatLab to find the angular position and the \( x \) displacement from equilibrium, (see Appendix A). Using both the Simulink models for Phase One, a comparison graph of the Working Model Data and the Lumped Mass Equations for \( \phi \) and \( x \) displacements was created (see Figures 27 and 28).

Figure 27-- Phase 1: Phi Positional Comparison
The Phi Lump Mass Approximation is a good representation of the Working Model Results. However the end results tend to differ slightly. At about .075 seconds, Alpha becomes less than phi and equation 23 is utilized. The Differences in the X Position Graph can be accounted for as the pin bounces from one side of the slot to the other. A reason for the difference may be because the inertia term, $m\ddot{X}_{mc}$, for the mass center was approximated by $m\ddot{X}$ where X is the pin position (see Appendix D).
For Phase Two both angles $\alpha_1$ and $\alpha_2$ were required for solving the model. For $\alpha_1$ the same setup was used as in Phase One (see Figure 25 and Equation 20). However for $\alpha_2$, Figure 30 was utilized. This diagram was then used for finding equation 24.

\[
\alpha_2 = \tan^{-1}\left( \frac{L_8 - L_5 \sin \phi - L_7 \cos \phi}{L_6 - L_5 \cos \phi} \right) \tag{24}
\]

The system equations for Phase Two were derived from the model shown in Figure 29 and are listed below.

\[
I \ddot{\phi} = wl \sin \phi - F_1 \sin(\phi - \alpha_1)L_2 - F_1 \cos(\phi - \alpha_1)L_1 + F_2 \sin(\phi - \alpha_2)L_2 + F_1 \cos(\phi - \alpha_2)L_1 \tag{25}
\]

\[
m \ddot{X} = -kX + F_1 \cos \alpha_1 + F_2 \cos \alpha_2 \tag{26}
\]

Using these system equations a Simulink model was created in MatLab (see Appendix A). This Simulink model was then used to find phi’s angular position and the x displacement (see Figures 31 and 32).
The Lump Mass Phi Results are almost identical to those that Working Model produced; notice the scale on Figure 31 was .005 radians. The greatest difference between the two models is only .01 radians. For The X Displacement Comparison, the timing on the moment of the pin differs but similar results are shown. A reason for the difference may be because the inertia term, $m \ddot{X}_{mc}$, for the mass center was approximated by $m \ddot{X}$ where X is the pin position (see Appendix D).
For Phase Three, only angle $\alpha_2$ was necessary for the analysis and was obtained from Phase Two, (see Figure 33 and Equation 25). The system equations for Phase Three were derived from the model shown in Figure 30 and are listed below.

\begin{align*}
I \ddot{\phi} &= -wl \sin \phi + F_2 \sin(\phi - \alpha_2)L_2 + F_2 \cos(\phi - \alpha_2)L_1 \\
mx &= -kx + F_2 \cos \alpha_2
\end{align*}

(27)  
(28)

Using these system equations a Simulink model was created in MatLab, (see Appendix A). Please note that for the purpose of this model, theta is equivalent to phi. To find the phi’s angular position and the x displacement as compared to the Working Model Results, see Figures 34 and 35.
The Lumped Mass Phi Position Results are a smooth line approximation of the Working Model Results and only differ slightly at the end. While the Working Model Results for the X displacement tend to oscillate in value, the Lumped Mass Results tend to the maximum displacement value quickly. A reason for the difference may be because the inertia term, $m\ddot{X}_{mc}$, for the mass center was approximated by $m\ddot{X}$ where X is the pin position (see Appendix D).
Finally, all three phases were combined and compared to Working Model. Figure 36 shows, that the Lumped Mass Equations and Working Model Results follow relatively the same path.

Figure 36--Working Model and Lumped Mass Results of Phi Position for all Three Phases

Overall the Phi Lumped Mass Simulink Results are good approximations of the Working Model Results. Both methods exhibit similar shapes. This therefore suggests that the phi positional representation of the Working Model Results accurately depicts the action of the Hopper’s motion.

Figure 37-Working Model and Lumped Mass Results of X Displacement for all Three Phases
Figure 37 shows the combined phase as compared to Working Model for the X direction displacement. The Lumped Mass X Displacement Results loosely follows the Working Model Results. This is not as precise as the Phi positional Results. The main reason for the discrepancies of the two plots is the approximate nature of the Lumped Mass Equations (See Appendix D).

3.4 Alexander’s Equations for Design of the EAP Hopper

For preliminary design of the EAP Hopper, Alexander’s Equations (described in Section 2.4.2) were utilized. The hopping height, velocity, and acceleration were developed for the designed Hopper. Table 6 shows the assumptions made for this analysis, which are based on the actual materials in the built Hopper. The equations numbers are shown.

| Table 6 – EAP Hopper Assumptions Used in Alexander’s Equations for an Ideal Hop |
|-----------------|----------|--------|--------|
| Variable        | Symbol   | Value  | Units  |
| Mass of base    | m₁       | .79    | grams  |
| Mass of upper leg | m₂      | .72    | grams  |
| Mass of lower leg | m₃     | .66    | grams  |
| Equation 14     | m₄       | 1.38   | grams  |
| Equation 15     | m₅       | 5.98   | grams  |
| Equation 16     | m₆       | 15.18  | grams  |
| Equation 17     | m₅total | 2.17   | grams  |
| Leg distance    | s        | .04    | meters |
| Take off angle  | θ        | Π/4    | radians |
| Equation 12, Muscle Moment | T | .00004 | N |

Using the assumptions made in Table 6 and equations 4 through equations 7, Table 7 was completed. Both the instantaneous and average angular velocities and accelerations are shown in the table. For the instantaneous motion values, the average velocity and acceleration were taken from Working Model’s Results of the lower leg swing in the Third Phase only. For the average motion values, the average velocity and accelerations were taken
from Working Model’s Results of the entire hop. Both the instantaneous and average motions are considered for comparison to the other theoretical methods used.

Table 7 – Motion results from Alexander’s Equations for the EAP Hopper

<table>
<thead>
<tr>
<th>Equation</th>
<th>Symbol</th>
<th>Instantaneous Value</th>
<th>Average Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assumed</td>
<td>Take off angular velocity, ( \dot{\theta} )</td>
<td>3.43</td>
<td>.251</td>
<td>rad/s</td>
</tr>
<tr>
<td>Assumed</td>
<td>Take off angular acceleration, ( \ddot{\theta} )</td>
<td>112.19</td>
<td>34.52</td>
<td>rad/s²</td>
</tr>
<tr>
<td>Eq 5</td>
<td>Vertical displacement, ( y )</td>
<td>.0566</td>
<td>.0566</td>
<td>m/s</td>
</tr>
<tr>
<td>Eq 6</td>
<td>Vertical velocity, ( \dot{y} )</td>
<td>.194</td>
<td>.014</td>
<td>m/s</td>
</tr>
<tr>
<td>Eq 7</td>
<td>Horizontal displacement, ( x )</td>
<td>.0283</td>
<td>.028</td>
<td>m/s</td>
</tr>
<tr>
<td>Eq 8</td>
<td>Horizontal velocity, ( \dot{x} )</td>
<td>-.097</td>
<td>.007</td>
<td>m/s</td>
</tr>
<tr>
<td>Eq 13</td>
<td>Take off acceleration, ( \ddot{y} )</td>
<td>11.77</td>
<td>12.92</td>
<td>m/s²</td>
</tr>
<tr>
<td>Eq 18</td>
<td>Vertical Force to accelerate body, ( F_{\text{ground}} )</td>
<td>3.66</td>
<td>1.95</td>
<td>N</td>
</tr>
<tr>
<td>Eq 19</td>
<td>Height of Jump, ( H_{\text{height}} )</td>
<td>9e-4</td>
<td>5e-6</td>
<td>m</td>
</tr>
</tbody>
</table>

To demonstrate the feasibility of the average motion values acquired from Alexander’s Equations, the Universal Equations were used. Using the same velocity found by the Alexander’s Equations, the Universal Equations were used to complete Table 8.

Table 8 – Average Motion Results Comparison for the EAP Hopper

<table>
<thead>
<tr>
<th>Average Motion</th>
<th>Alexander’s Equations Results</th>
<th>Universal Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Angular Velocity, rad/s</td>
<td>.35</td>
<td>(.35)</td>
</tr>
<tr>
<td>% Difference</td>
<td>0</td>
<td>na</td>
</tr>
<tr>
<td>Average Angular Acceleration, rad/s²</td>
<td>323.75</td>
<td>38.28</td>
</tr>
<tr>
<td>% Difference</td>
<td>0</td>
<td>88.7</td>
</tr>
</tbody>
</table>

The Universal Equations are intrinsically not very accurate for jumping because they do not consider the catapulting design; however, this is a crude assessment of objects in motion.
3.5 Results of Design Analysis for the EAP Hopper

The three instantaneous analytical methods for describing the motion of the EAP Hopper were compared in Table 9. The biggest discrepancy was the acceleration. It rapidly changes throughout the kick; therefore, it was very difficult to determine the correct value at different moments in time.

<table>
<thead>
<tr>
<th>Motion</th>
<th>Alexander’s Equations Results</th>
<th>Working Model Results</th>
<th>Lumped Mass Equations Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular Velocity, rad/s</td>
<td>4.85</td>
<td>11.26</td>
<td>18.91</td>
</tr>
<tr>
<td>% Difference</td>
<td>131.0</td>
<td>0</td>
<td>75.9</td>
</tr>
<tr>
<td>Angular Acceleration rad/s²</td>
<td>294.3</td>
<td>102.4</td>
<td>75.74</td>
</tr>
<tr>
<td>% Difference</td>
<td>187.4</td>
<td>0</td>
<td>26.0</td>
</tr>
</tbody>
</table>

In Table 9, the Alexander’s equation accounts for the average motion throughout the last phase of motion and the Working Model and Lumped Mass Equations are the instantaneous values in the third phase. This could account for the difference. With the instantaneous analytical results in agreement that a hop could be produced, the Hopper was constructed as specified in the component drawings (see Appendix B).

3.6 EAP Actuator Design Issues

When the EAP actuators were put in a cantilever configuration, they worked consistently (see Figure 38). Initially, the EAP Actuator was connected to a tab at one end with the other end free. In this cantilevered configuration, the EAP Actuator behaved properly and performed repeatedly. The bending occurs from the flow of current moving cations up the positive side and back down the negative side. The EAP Actuator bends toward the positive side.
However, when the free end was attached to the Hopper’s leg, motion was not produced. The following are problems and solutions encountered while constructing the EAP Actuator. The following issues are addressed: Eliminating Grounding Issues, Attaching The Free End, Current and Force Testing, and Alternate Solutions.

3.6.1 Eliminating Grounding Issues

The EAP Actuator was connected to the chassis of the Hopper, and the free end was epoxied--using JB Weld--to another tab (see Figure 39). The actuator did not activate in this configuration. It did not appear to fail because of insufficient force, but rather it did not actuate at all. It appeared that the EAP Actuator was “short circuited”. Bubbles, which are generally seen above voltages of 1.23 volts, were not seen on the EAP material no matter what voltage was applied.
To alleviate this problem several situations were considered. Due to the fiberglass and metal screw make up of the Hopper, the resistivity of the Hopper’s legs was compared to the EAP Actuator resistivity. The EAP Actuator had a 13.7 ohms resistance and a current draw of 391.2 mA. One leg of the Hopper, when measured, had a very high resistance that could be considered an infinite resistance. This did not account for the short-circuiting of the actuator setup.

Another circuit problem could be from the JB Weld itself. According to the JB Weld website, the epoxy contains small metallic pieces. Since the entire end (both positive and negative sides) of the EAP materials was placed in the JB Weld, this could be the source of the short-circuiting. To solve this issue, two items were changed: the attachment positioning and the epoxy type. In the new arrangement, the EAP material would no longer contact the fiberglass tab. Instead a plastic piece was attached perpendicular to the tab (see Figure 40). This orientation allowed for only one side of the EAP material to contact the epoxy. Secondly, the JB Weld was removed from the set up. EPOXI-PATCH epoxy was used to secure the free end of the EAP material to the plastic tab (see Figure 40). The EPOXI-PATCH was only applied to one side of the EAP material and applied to the plastic only.
This new setup did not work either because the colorant of the EPOXI-PATCH had metal particles in it. Also, putting a smaller force of the tip of the EAP Actuator was considered. The weight of the current tab setup could be too great for the actuator; however, no check was done on this. This directed the focus of the actuator design back to the basics of the EAP Actuator.

3.6.2 Attaching the Free End of the EAP

To better understand the EAP Actuator, a three-layer material should be considered: two layers of platinum with a Nafion layer in the middle. The Nafion layer is non-conductive by itself and it looks like a piece of clear acetate. This three-layer configuration is similar to a parallel plate capacitor (see Figure 41). The voltage difference between the two plates can be expressed in terms of the work done on a positive test charge q when it moves from the positive to the negative plate [12]. The voltage and current behavior can be seen in Figure 42. For an EAP Actuator .055 m X .004 m large, a capacitance meter found an estimated capacitance of 1.58 μfarads. This was to be used as a baseline for future calculations.
To eliminate all current and weight problems, three setups were constructed to test the operation of the EAP Actuator (see Figure 43). These setups were used to determine whether the EAP was able to actuate with a small amount of force (the dab of Epoxy) applied to the tip. The epoxy used for all future setups was West System Brand Mix 105 Resin and 205 Hardener, which created a clear waterproof seal. This eliminates any interaction with the metal particles in conductive epoxies.

Test Setup One contained a small dab of epoxy on the platinum layer of the EAP Actuator. This is similar to the previous test setup, but with less resistance as the weight was lower than the previous set up (see Figure 43). It did not actuate with any voltage.
Test Setup Two was used to determine if attaching the Epoxy directly to the Nafion inner layer has any effect on the actuation of the material (see Figure 43). A section of the metallic layer was removed using a mat knife. The dab of Epoxy was applied to the Nafion and left to dry. This setup worked reliably with the same level of voltage as without the ball of epoxy. It was very repeatable. A second dab of epoxy was applied to the epoxy to increase the amount of tip force. This again actuated reliably and repeatedly.

Finally for Setup Three, four EAP strips were stacked together and secured with Saran Wrap (see Figure 43). Then an electrode was applied to each end of the stack. During a phone conversation with Matt Bennett, he suggested stacking the materials to create a greater force. This was very unstable and was hard to keep the four materials together. In addition, the stack would not reliably actuate. This is not a solution for the use in the Hopper. A better securing method would need to be developed. No data was taken for this Setup.
An interesting find in these tests was that as the EAP Actuator bent from a 90-degree angle to a straight 180 angle, the current increased rapidly. Using a 4 volts constant input, at the point where the material was straight, the current spiked to above 200 mA. The current then decreased as it bent toward the other side.

3.6.3 Current Testing of the EAP Actuator Over Time

With the previous finding that the current was not constant throughout the actuation, a circuit to model the EAP material was constructed (see Figure 44). It was thought that the best way to measure the capacitance flow across the EAP Actuator for a certain voltage over time was through the use of data acquisition software. However, the actual setup did not behave as the model predicted. The SPI Silver Epoxy electrode created a resistance of 1000 ohms across the EAP material. This added resistance, the slow settling time of the EAP material, and the need for a more precise Data Acquisition Apparatus, made it impossible to use this model to evaluate the capacitance across the EAP actuator.

![Figure 44 -- Theoretical Model Circuit Diagram for Data Acquisition](image)

The system used the input voltage, \( V_{in} \), as 4 volts.

Also, the resulting current time curve from this model would ultimately decay to 0 milliamps because this single capacitor model would not allow current to bypass the capacitor. Through attempted data acquisition trials, it was observed that the current never dropped to 0 milliamps. Therefore another model was needed to depict the current flow through the circuit.
To remove any excess resistance created by the silver epoxy electrode, two new fixtures were constructed. In Mallavarapu's study of Feedback Control of Ionic Polymers, he used a spring-loaded kitchen cabinet securing bracket to hold the EAP material [16]. Using this idea, Dry and Wet Test stands were constructed. Both fixtures held the EAP material in a cantilevered position. One positioned the Actuator in air and the other held it in a bath of de-ionized water (see Figure 45). The fixture was fitted with both a positive and negative wire electrode. The EAP material was sandwiched between the two wires and the spring-loaded brackets.

Figure 45 – Wet and Dry Test Fixtures

Both a Wet Test and Dry Test were conducted. A video camera was used to show the movement of the EAP Actuator and the voltage and current draw readout on the power supply. Then using the video and a frame-by-frame advancement, graphs were created (see Appendix C).

Figure 46 shows four different plots for the Wet Test Setup using a 4-volt input. Looking at the graph, the actuation initially required a large amount of current and then dropped off rapidly by 100 to 200 milliamp. Three of the plots are good runs, where the EAP material effectively actuated by moving a large displacement. Fewer bubbles were seen throughout these setups as compared to the poor runs. The sixth trial was a bad run because the EAP material did not actuate well. As with other bad runs, a spiking of current was present. In Figure 46, the spiking can be seen as the $6^{th}$ through $9^{th}$ data points do not follow the general
decay trend of trial. In general, the runs that did not exhibit a large spike in current performed better than those that did. Also, in general, the initial current value drawn by the EAP material dropped to around 60% of that value at steady state.

![Wet Test Setup Using 4 Volt Input with Three "Good Runs" and One "Bad Run"

Figure 46 – Wet Current Test Setup Using 4 Volts

In Figure 46, the trials begin at different initial current draws. This finding initiated questions about hydration and initial curvature of the EAP material, and their effects on initial current draw. The initial curvature and amount of rotational displacement was recorded for each of these trials. The start and end curvature are pictorially represented in Table 10. Also, an estimated rotational displacement value is present. This data was collected by visual inspection of the video recording of the Wet Test Setup. From Table 10, no direct correlation between rotational displacement and curvature as related to current draw can be seen. This should be further studied for a direct correlation.
To best understand and predict the current draw over time of the EAP material, the circuit diagram in Figure 47 was proposed. In the circuit diagram, the addition of the second resistor in parallel with the capacitor, allows for the current to be non-zero even as the capacitor becomes discharged. This best explains the offset, which is seen in the steady state current value in Figure 46.

Looking at Figure 47, the following circuit equations can be created:

$$V(t) = \frac{V_{in} - V_{out}}{R_1}$$  \hspace{1cm} (29)
\[ i(t) = c \frac{d}{dt} V_{out} + \frac{1}{R_2} V_{out} \]  \hspace{1cm} (30)

Combining these equations and using the Laplace Transformation, a formula for the transformed current as function of voltage can be created:

\[ I(s) = \frac{1}{R_1} \left( s + \frac{1}{R_2 C} \right) V_{in}(s) \]  \hspace{1cm} (31)

Assuming that \( V_{in}(s) \) is a step input and \( A \) is the magnitude of the input, then the following equation results:

\[ I(s) = \frac{A}{R_1} \left( s + \frac{1}{R_2 C} \right) \]  \hspace{1cm} (32)

Then using the Final Value Theorem and taking the limit as \( s \) approaches 0 at steady state, the steady state current equation becomes:

\[ i_{ss} = \frac{A}{R_1 + R_2} \]  \hspace{1cm} (33)

Note that capacitance plays no role in achieving steady state. After making the following assumptions in equation 30, equation 35 results in the following:

\[ \tau_1 = R_2 C \]  \hspace{1cm} (34)

\[ \tau_2 = \frac{R_1 R_2 C}{R_1 + R_2} \]  \hspace{1cm} (35)

\[ C_1 = \frac{A}{R_1} \]  \hspace{1cm} (36)

\[ I(s) = \frac{C_1 (s + \frac{1}{\tau_1})}{s(s + \frac{1}{\tau_1})} \]  \hspace{1cm} (37)

Then through the Inverse Laplace Transformation and manipulation, the following function can be used to determine the action of the EAP actuator’s current throughout bending:

\[ I(t) = A_1 + A_2 e^{-\tau_2} \]  \hspace{1cm} (38)
where:  

\[ A_i = \frac{C_1 \tau_2}{\tau_1} \]  

(40)

\[ A_2 = C_1 - \frac{C_1 \tau_2}{\tau_1} \]  

(39)

To best understand the outcome of this current time relationship, the equations (34) and (35) can be combined to find the optimal ratio for \( R_2 \) and \( R_1 \), which can be seen below:

\[ \tau_2 = \frac{R_1}{R_1 + R_2} \tau_1 \]  

(41)

Using Figure 46, the three good data runs were fitted with Excel’s Best Fit function. The graphs were shifted to meet the x-axis for the final point. Figure 48 shows these Results.

Looking at the Figure 48, trial 8 had the most actuate Best Fit curve with a \( R^2 \) value of .9726. Since plots did have \( R^2 \) values that were as high, the Wet Setup was completed again to acquire a larger quantity of data and more accurate data. For the Current Test Two, the
samples used were freshly boiled and used for no more than five trials. New wires were used in the setup as well. Data was collected in the same fashion as before. The eight best trials were plotted and the results can be seen in Figure 49. The trials are numbered for the sample number and the run number.

![Figure 49 - Wet Test Setup Current Test Two](image)

The plots in Figure 49 were then estimated and normalized. Using Excel's Best Fit function the plots were estimated and the best fit equations and $R^2$ values can be seen in Table 11. The plots were normalized in Excel and can be seen in Figure 50. There is not correlation between trails. Also, no correlation between same sample trials can be seen. In Table 12, the differences between the start and finish currents are shown. No correlation is seen.
Table 11 -- Best Fit Equation and $R^2$ Values for Current Test Two

<table>
<thead>
<tr>
<th>Trial Number</th>
<th>Best Fit Equation</th>
<th>$R^2$ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.10</td>
<td>$y = -11.347 \ln(x) + 133.34$</td>
<td>0.8953</td>
</tr>
<tr>
<td>3.2</td>
<td>$y = -10.809 \ln(x) + 103.83$</td>
<td>0.993</td>
</tr>
<tr>
<td>3.11</td>
<td>$y = -15.286 \ln(x) + 105.43$</td>
<td>0.9652</td>
</tr>
<tr>
<td>5.11</td>
<td>$y = -14.294 \ln(x) + 97.141$</td>
<td>0.9802</td>
</tr>
<tr>
<td>3.6</td>
<td>$y = -9.4307 \ln(x) + 74.763$</td>
<td>0.8675</td>
</tr>
<tr>
<td>5.12</td>
<td>$y = -15.495 \ln(x) + 74.944$</td>
<td>0.988</td>
</tr>
<tr>
<td>4.2</td>
<td>$y = -12.388 \ln(x) + 73.54$</td>
<td>0.8967</td>
</tr>
<tr>
<td>3.9</td>
<td>$y = -8.6347 \ln(x) + 42.019$</td>
<td>0.9129</td>
</tr>
</tbody>
</table>

Normalized Best Trials

Table 50 -- Normalized Best Trials for Test Two
Table 12 – Difference of Start and Finish Current Levels

<table>
<thead>
<tr>
<th>Trial Number</th>
<th>Start Value</th>
<th>Finish Value</th>
<th>Difference</th>
<th>Percent Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2</td>
<td>165</td>
<td>109</td>
<td>56</td>
<td>66.1</td>
</tr>
<tr>
<td>3.6</td>
<td>125</td>
<td>84</td>
<td>41</td>
<td>67.2</td>
</tr>
<tr>
<td>3.9</td>
<td>142</td>
<td>78</td>
<td>64</td>
<td>54.9</td>
</tr>
<tr>
<td>3.10</td>
<td>130</td>
<td>69</td>
<td>61</td>
<td>53.1</td>
</tr>
<tr>
<td>3.11</td>
<td>130</td>
<td>55</td>
<td>53</td>
<td>42.3</td>
</tr>
<tr>
<td>5.11</td>
<td>100</td>
<td>62</td>
<td>38</td>
<td>62.0</td>
</tr>
<tr>
<td>5.12</td>
<td>109</td>
<td>41</td>
<td>68</td>
<td>37.6</td>
</tr>
<tr>
<td>4.2</td>
<td>62</td>
<td>30</td>
<td>32</td>
<td>48.4</td>
</tr>
</tbody>
</table>

Looking at Figure 49, a simulation using Equation 38 was setup in Matlab. A 4 volt step input, A, and a 1.58 microfarad capacitance, C, were assumed. R1 and R2 were varied for the best approximation of the recorded data (see Table 13 for R1 and R2 resistor results).

For the Second Current Test, the initial curvature and rotation displacement seen was not recorded because, in general, the material began in a straight position and rotated 35 degrees. Since all the materials used were freshly boiled and extremely hydrated, this may be an indication that hydration has a role in determining the initial curvature of the material. Therefore, this initial curvature may have a correlation with the initial current draw required to actuate the EAP material. This implicit curvature-current correlator can be seen by the lower initial current draws in the second test, which has straight initial curvature as compared to the larger initial current draws seen in the first test which has bent initial curvature. This phenomenon should be further studied.

Table 13 – R1 and R2 Resistor Values Utilized in Equation 38

<table>
<thead>
<tr>
<th>Trial</th>
<th>3.10</th>
<th>3.2</th>
<th>3.11</th>
<th>5.11</th>
<th>4.2</th>
<th>3.6</th>
<th>5.2</th>
<th>3.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1 Value</td>
<td>0.0250</td>
<td>0.0300</td>
<td>0.0260</td>
<td>0.0280</td>
<td>0.0340</td>
<td>0.0370</td>
<td>0.0350</td>
<td>0.0580</td>
</tr>
<tr>
<td>R2 Value</td>
<td>0.0090</td>
<td>0.0170</td>
<td>0.0260</td>
<td>0.0290</td>
<td>0.0400</td>
<td>0.0290</td>
<td>0.0550</td>
<td>0.0770</td>
</tr>
<tr>
<td>R1/R2 Ratio</td>
<td>2.7778</td>
<td>1.7647</td>
<td>1.0000</td>
<td>0.9655</td>
<td>0.8500</td>
<td>1.2759</td>
<td>0.6364</td>
<td>0.7532</td>
</tr>
<tr>
<td>Steady State Value, eq. 31</td>
<td>117.6471</td>
<td>85.1064</td>
<td>76.9231</td>
<td>70.1754</td>
<td>54.0541</td>
<td>60.6061</td>
<td>44.4444</td>
<td>29.6296</td>
</tr>
<tr>
<td>$t_1/t_2$ ratio, eq. 39</td>
<td>1.3600</td>
<td>1.5667</td>
<td>2.0000</td>
<td>2.0357</td>
<td>2.1765</td>
<td>.7838</td>
<td>2.5714</td>
<td>2.3276</td>
</tr>
</tbody>
</table>
Figure 51 shows the Inverse Laplace Transform of equation 32 assuming zero initial conditions. The dashed lines are the equation 32 plots and the actual acquired data is solid lines. The R1 and R2 values were taken from Table 13. The eight best trials were Best Fit in Excel and compared to the Inverse Laplace Transform of Equation 32 (see Figure 51). For each individual case, the Excel Best Fit Data, Inverse Laplace Transform of Equation 32, and the actual recorded data are shown in Figure 52.

![Comparison of Excel Best Fit and Circuit Diagram Equations](image)

Figure 51 -- Combined Excel Best Fit and Inverse Laplace Transform of Equation 32 Results
Comparison Of Current Circuit and Lab Data for Trial 3.10

Comparison Of Current Circuit and Lab Data for Trial 3.2

Comparison Of Current Circuit and Lab Data for Trial 3.11

Comparison Of Current Circuit and Lab Data for Trial 5.11

Comparison Of Current Circuit and Lab Data for Trial 4.2

Comparison Of Current Circuit and Lab Data for Trial 3.6

Comparison Of Current Circuit and Lab Data for Trial 5.2

Comparison Of Current Circuit and Lab Data for Trial 3.9

Figure 52 -- Best Fit For Eight “Good” Trials
The results of Figures 51 and 52 show that the model in Figure 47 is an effective method for predicting the steady state outcome of the EAP actuator based on the input voltage and resistance values. Further study should be conducted on this finding.

In Figure 53, the Dry Setup using a 4 volt input can be seen. This is an excellent actuation that moves from one radial extreme to the other—the EAP material made a full 180 rotation. This graph is full of small current spikes that are not present in the Wet Test Setup. Also, there is less overall current change throughout the test; initially the current is around 240 milliamp and then drops to about 180 milliamp. This is far less than the 200 milliamp drop seen in the Wet Test Setup.

![Dry Test Setup Using 4 Volt Input with Good Movement Seen](image)

**Figure 53 – Dry Current Test Setup Results**

In addition, the general trend of the Dry Test Setup Graph is different from the Wet Test Setup Graph. It should be noted that as time increases, the current drops and then gradually increases. This is different than the gradually decreasing current levels in the Wet Test Setup. The Wet Test Setup seems to follow the general plot of a parallel plate capacitor more than the Dry Test Setup.
Comparing the graphs in Figure 50 and 53, the Dry Test Setup initially drew more current than the Wet Test setup. This is a significant amount difference and could affect the usage of the EAP Actuator in conjunction with power supplies. In addition, the erratic-ness of the Dry Test could produce difficulties in choosing a power supply. Also, this Dry Test Plot may explain why a current spike seen in the silver epoxy electrode actuation setup, which was also conducted in air and not DI water. The use of DI water seems to make the current draw more constant.

3.6.4 Force Testing

Another test was performed to determine the amount of force this setup could output. A vertical force test was setup using a digital balance that has an accuracy of .0001g (See Figure 54). Using a piece of EAP materials that was 5 mm wide and 20 mm long, the average value of the force was .005 grams when the sample bent down the contracting scale.

![Figure 54—Force Balance Setup](image)

Using the average .005-gram deflection, Newton’s law can be used to calculate the force. For this EAP Actuator the average force output was .539 mN. The range of values was from 1.166 to .167 mN for 10 trials. This is in the range of what was suggested by Bennett. This suggests that the EAP Hopper, when utilized with the EAP Actuator, would not meet the
assumptions made for all theoretical calculations presented earlier. A redesigned lighter Hopper would be necessary.

The use of a laser vibration meter and high frequency data acquisition software would better define the EAP Actuator. The more precise data acquisition software could better articulate the current draw and capacitance levels of the EAP Actuator. The vibration meter could measure the displacement of the material in response to the current drop over time. However as a rough estimate, this is an effective method for collecting this data.

3.6.5 Alternate Actuator Solutions

A Nitinol Shape Memory Alloy Linear Actuator was tested independent of the Hopper. Using 1 volt, the linear actuator was able to contract almost instantly. While this could be beneficial to the Hopper, the time it took to return to its original position was substantial. A two opposing actuator setup might speed up the recovery time. However, the weight of the actual actuator is considerable, and eight actuators would be necessary for the Hopper in this orientation. Ultimately since the Hopper requires a lightweight relatively quick contraction and release, the SMA actuator was not a feasible solution to the actuator issues.

3.7 EAP Hopper Design with EAP Actuator Best Orientation

Since the EAP Hopper’s simulations predict its ability to leap and the actuator’s circuit issues were resolved, the potential for such a device can be imagined. In Figure 55 the proposed best orientation of the EAP Actuator is shown. From Section 3.6.2 the Test Setup Two--where the EAP’s platinum layer is removed before applying the nonconductive epoxy directly to the Nafion layer--will allow for repeatable results. Nonconductive epoxy should also be used at the electrode side of the Actuator to eliminate any possible interaction with the epoxy. In addition, the epoxy should be applied to a plastic tab to again isolate the EAP for any possible contact with the body of the Hopper.
Finally, the SPI Silver epoxy is a good, lightweight, and inexpensive material for creating the electrodes. While it does create a large resistance, it is still a good method for activating the EAP material.

The Hopper Leg setup depicted in Figure 55 and the force produced by the EAP Hopper should show good results. Figure 56 shows the potential orientations of an assembled hopper legs with EAP Actuator attached. In Figure 57, the potential construction of the entire EAP Hopper is shown.
According to the Alexander's Equations and the average leg kick velocities found using Working Model, the Hopper with .539 mN of force would have a hop height of .91 mm. This therefore suggests that the hopper would have to be reduced in size and redesigned to jump efficiently.
Section 4 The Grasshopper Hopping Robot Design and Jump Analysis with Use of the Pneumatic Actuator

The Hopper was designed to meet the criteria of the EAP Actuator. However, it was not implemented because of actuator issues discussed in Section 3.6. To best test the potential of the Hopper built for the EAP Actuator, a Pneumatic Hopper was considered. The EAP Actuators were replaced by four pneumatic linear actuators to simulate their action. The Hopper chassis designed for the EAP Actuator was utilized (See section 3.1). This section discusses: the Pneumatic Hopper’s Design and Components; The Pneumatic Hopper’s Simulation and Results; The Pneumatic Hopper’s Test Setup and Results; and Pneumatic Hopper Results: Dynamics and Motion Comparison.

4.1 Pneumatic Hopper’s Design and Components

The pneumatic actuators utilized in the Pneumatic Hopper were the CJP series from SMC [26]. They were the smallest available actuators with a bore size of 6 mm (see Figure 58). The pneumatic actuators had a minimum pressure of 2 bars and operating pressure of 7 bars. To simulate the extensor muscle a 15 mm stroke was used, and for the flexor muscle a 20 mm stroke was used.

![Figure 58 -- SMC CJP Pneumatic Linear Actuator [26]](image)

A diagram for the airflow of the Pneumatic Hopper can be seen in Figure 59. To activate the four pneumatic actuators, two MAC Valves were utilized. The Valves were activated by the same relays shown in section 3.1. However, only two relays were required.
To attach the pneumatic actuators to the Hopper, eight L-brackets were required. These small metal components utilized the threads on the actuators. Their minimal additional weight was accounted for in the weight of the leg. The Flexor and Extensor Muscles attached to legs of the Pneumatic Hopper can be seen in Figure 60.

The addition of the pneumatic components created a huge design issue: weight. The Hopper with the four pneumatic actuators weighed 83.9 grams. The use of the lightweight fiberglass no longer seemed to be a critical design feature. The EAP Hopper’s chassis weight was 4.96 grams, which was only a small portion of the total weight of the Pneumatic Hopper. When
the Hopper was attached to the MAC Valve, the hosing added an additional 27.1 grams. The Hopper was weighted before and after attaching hoses. This is 32.38 percent of additional weight. This weight limits the possibility of hop and creates issues when calculating jump potential. For purposes of calculation, the additional hose weight was added to the base weight.

For best hop height, 60 psi was used before the split in the manifold. The final results can be seen in Figure 61. The actual force exerted by the actuators at 60 psi is 3.47 N.

![Figure 61-- Pneumatic Hopper with Hoses Attached](image)

4.2 The Pneumatic Hopper’s Simulation and Results

Similar simulations were completed on the Pneumatic Hopper as the EAP Hopper. The Working Model, MatLab, Alexander Equations, and Universal Dynamic Equations are all considered for the Hopper. In all Pneumatic Hopper Simulations the 27.1 grams of hosing weight was added to the Hopper’s base weight. This assumption caused weight of the base component of the Pneumatic Hopper to be 27.89 grams instead of .79 grams in the EAP Hopper. This causes the total Hopper weight to increase from 83.9 to 100.99 grams.

The Working Model Simulation conducted for the EAP Hopper was completed for the Pneumatic Hopper (see Section 3.2). The setup was changed to accommodate the additional weight and power supplied by the pneumatic actuator. The times and spring constant were also changed for the three phases, which can be seen in Table 14. For the new setup see
Figure 62 and for new properties used in this simulation see Table 14. The base component weight is not present in this simulation.

![Diagram of working model simulation for pneumatic actuator constraints]

**Table 14 -- Changed Properties of the Pneumatic Actuator**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of Lower leg</td>
<td>13.85</td>
</tr>
<tr>
<td>Weight of Upper leg</td>
<td>27.7</td>
</tr>
<tr>
<td>Spring Constant, K</td>
<td>10</td>
</tr>
<tr>
<td>Actuator Force</td>
<td>3.479</td>
</tr>
</tbody>
</table>

As with the previous simulation, when the lower leg was perpendicular to the ground, the Pneumatic Hopper was assumed to jump. These results of acceleration are found in Table 15.
Table 15 – Pneumatic Hopper Working Model Results for Lower Leg the Instant Before Hop

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity vertical direction</td>
<td>Vx</td>
<td>2.2</td>
<td>m/s</td>
</tr>
<tr>
<td>Velocity horizontal direction</td>
<td>Vy</td>
<td>.073</td>
<td>m/s</td>
</tr>
<tr>
<td>Velocity</td>
<td></td>
<td>2.2</td>
<td>m/s</td>
</tr>
<tr>
<td>Angular velocity</td>
<td>( \psi )</td>
<td>108.8</td>
<td>rad/s</td>
</tr>
<tr>
<td>Acceleration vertical direction</td>
<td>Ax</td>
<td>44.7</td>
<td>m/s²</td>
</tr>
<tr>
<td>Acceleration horizontal direction</td>
<td>Ay</td>
<td>225.9</td>
<td>m/s²</td>
</tr>
<tr>
<td>Average Acceleration</td>
<td></td>
<td>230.4</td>
<td>m/s²</td>
</tr>
<tr>
<td>Angular Acceleration</td>
<td>( \Phi )</td>
<td>-305.3</td>
<td>rad/s²</td>
</tr>
</tbody>
</table>

To check the feasibility of the Working Model Results, The Lumped Mass Approximation Equations were compared to the Working Model Results in the same fashion as before. The Lumped Mass Model used is an approximation of the actual model (see Appendix D). For the Pneumatic Hopper, the weight and force were changed in the Lumped Mass Model. Also the time of each phase changed because of the increase force of the actuators. The first “drawback” phase was considered from time 0 to .010 seconds. The second phase, the cocking phase, occurs from .010 to .013 seconds. Finally, the third phase, the kicking phase, is from .013 to .068 seconds. The resulting Three Phase Comparisons for Phi Position and X-Displacement can be seen in Figures 63 and 64.

![Figure 63](image-url)

Figure 63—Pneumatic Hopper’s Working Model and Lumped Mass Approximation Results of Phi Position for all Three Phases
Figure 64—Pneumatic Hopper’s Working Model and Lumped Mass Approximation Results of X-Displacement for all Three Phases

These results are again a close approximation to the Working Model Results. The Phi Position Results again match very closely. The X Displacement Results are less close because approximations made in the study (see Appendix D).

Finally, Alexander’s Equations were used to determine the jump potential of the Pneumatic Hopper Setup. Table 16 shows the assumptions made for the Pneumatic Hopper to be used in both the instantaneous and average Alexander’s Equations.

Table 16 – Pneumatic Hopper Assumptions Used in Alexander’s Equations for an Ideal Hop

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of base</td>
<td>m₁</td>
<td>.02789</td>
<td>Kg</td>
</tr>
<tr>
<td>Mass of upper leg</td>
<td>m₂</td>
<td>.0139</td>
<td>Kg</td>
</tr>
<tr>
<td>Mass of lower leg</td>
<td>m₃</td>
<td>.0277</td>
<td>Kg</td>
</tr>
<tr>
<td>Equation 14</td>
<td>m₄</td>
<td>.0416</td>
<td>Kg</td>
</tr>
<tr>
<td>Equation 15</td>
<td>m₅</td>
<td>.2089</td>
<td>Kg</td>
</tr>
<tr>
<td>Equation 16</td>
<td>m₆</td>
<td>.5426</td>
<td>Kg</td>
</tr>
<tr>
<td>Equation 17</td>
<td>m&lt;sub&gt;total&lt;/sub&gt;</td>
<td>.0695</td>
<td>Kg</td>
</tr>
<tr>
<td>Equation 12, Muscle Moment</td>
<td>T</td>
<td>.139</td>
<td>N</td>
</tr>
</tbody>
</table>
Using the assumptions made in Table 14, the instantaneous velocity and acceleration of the downward swing of the lower leg were calculated. Table 17 shows the instantaneous motion of the lower leg. The angular motion used for these equations was the average taken from the Third Phase values only. These results are compared to other instantaneous velocities in Table 18.

### Table 17 – Alexander’s Equations using the Average Angular Velocities and Accelerations Taken From the Third Phase Used to Model the Pneumatic Hopper

<table>
<thead>
<tr>
<th>Equation</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assumed</td>
<td>Take off angular velocity, $\dot{\theta}$</td>
<td>74.31</td>
<td>rad/s</td>
</tr>
<tr>
<td>Assumed</td>
<td>Take off angular acceleration, $\ddot{\theta}$</td>
<td>528.61</td>
<td>rad/s²</td>
</tr>
<tr>
<td>Eq 3</td>
<td>Vertical displacement, $y$</td>
<td>0.566</td>
<td>m/s</td>
</tr>
<tr>
<td>Eq 4</td>
<td>Vertical velocity, $\dot{y}$</td>
<td>5.944</td>
<td>m/s</td>
</tr>
<tr>
<td>Eq 5</td>
<td>Horizontal displacement, $x$</td>
<td>0.283</td>
<td>m/s</td>
</tr>
<tr>
<td>Eq 6</td>
<td>Horizontal velocity, $\dot{x}$</td>
<td>-2.10</td>
<td>m/s</td>
</tr>
<tr>
<td>Eq 10</td>
<td>Take off acceleration, $\ddot{y}$</td>
<td>93.9</td>
<td>m/s²</td>
</tr>
<tr>
<td>Eq 15</td>
<td>Vertical Force to accelerate body, $F_{\text{ground}}$</td>
<td>5.76</td>
<td>N</td>
</tr>
<tr>
<td>Eq 16</td>
<td>Height of Jump, $H_{\text{height}}$</td>
<td>1.017</td>
<td>m</td>
</tr>
</tbody>
</table>

### Table 18 -- Comparison of Instantaneous Motion for the Pneumatic Hopper

<table>
<thead>
<tr>
<th>Instantaneous Motion</th>
<th>Alexander’s Equations Results</th>
<th>Working Model Results</th>
<th>Lumped Mass Equations Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity, rad/s</td>
<td>148.6</td>
<td>84.059</td>
<td>97.7</td>
</tr>
<tr>
<td>% Difference</td>
<td>43%</td>
<td>0</td>
<td>16%</td>
</tr>
<tr>
<td>Acceleration, rad/s²</td>
<td>1883.25</td>
<td>2154.6</td>
<td>173.5</td>
</tr>
<tr>
<td>% Difference</td>
<td>12.6%</td>
<td>0</td>
<td>100.9%</td>
</tr>
</tbody>
</table>

The discrepancy found in the Lumped Mass Acceleration can be accounted for by the rapid change in velocity. This variance can be seen in Figure 65. The Lumped Mass Equations are approximate in nature and the moment of inertia value, $I$, used for computation was for an approximate rectangle. However, Working Model computed the inertia based on the actual
leg geometry. This could account for difference between the Lumped Mass and Working Model Results.

![Figure 65– Phi Rotational Acceleration Plot of Lumped Mass Equation](image)

Also using the assumptions made in Table 16, the average velocity and acceleration of the lower leg swing were calculated. Table 19 shows the average motion of the lower leg. The angular motion used for these equations was the average taken from the entire hop’s velocity and acceleration values.

<table>
<thead>
<tr>
<th>Equation</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assumed</td>
<td>Take off angular velocity, $\dot{\theta}$</td>
<td>19.76</td>
<td>rad/s</td>
</tr>
<tr>
<td>Assumed</td>
<td>Take off angular acceleration, $\ddot{\theta}$</td>
<td>3035</td>
<td>rad/s²</td>
</tr>
<tr>
<td>Eq 3</td>
<td>Vertical displacement, $y$</td>
<td>.0566</td>
<td>m/s</td>
</tr>
<tr>
<td>Eq 4</td>
<td>Vertical velocity, $\dot{y}$</td>
<td>1.118</td>
<td>m/s</td>
</tr>
<tr>
<td>Eq 5</td>
<td>Horizontal displacement, $x$</td>
<td>.0283</td>
<td>m/s</td>
</tr>
<tr>
<td>Eq 6</td>
<td>Horizontal velocity, $\dot{x}$</td>
<td>-.559</td>
<td>m/s</td>
</tr>
<tr>
<td>Eq 10</td>
<td>Take off acceleration, $\ddot{Y}$</td>
<td>17.39</td>
<td>m/s²</td>
</tr>
<tr>
<td>Eq 15</td>
<td>Vertical Force to accelerate body, $F_{ground}$</td>
<td>2.76</td>
<td>N</td>
</tr>
<tr>
<td>Eq 16</td>
<td>Height of Jump, $H_{height}$</td>
<td>.036</td>
<td>m</td>
</tr>
</tbody>
</table>
To demonstrate the feasibility of the average motion results obtained from Alexander’s Equations, the results were compared to the Universal Equations for jumping (see Table 20). For the Universal Equations, the same velocity found from the Alexander’s Equations was used to find the average acceleration.

Table 20 -- Comparison of Analytical Average Motion Results for Actual Pneumatic Hopper

<table>
<thead>
<tr>
<th>Average Motion</th>
<th>Alexander’s Equations Results</th>
<th>Universal Motion Equations Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity, rad/s</td>
<td>27.95</td>
<td>(27.95)</td>
</tr>
<tr>
<td>% Difference</td>
<td>0</td>
<td>na</td>
</tr>
<tr>
<td>Acceleration, rad/s²</td>
<td>448.75</td>
<td>390.6</td>
</tr>
<tr>
<td>% Difference</td>
<td>0</td>
<td>79.2%</td>
</tr>
</tbody>
</table>

The reason for the discrepancy is that the Universal Equations do not take into account the geometry of the Hopper.

4.3 The Pneumatic Hopper’s Test Setup and Results

To evaluate the success of the Pneumatic Hopper, the following tests were conducted to determine height of hop, range of hop, and comparison to theoretical results. These tests were preformed on a relatively rough surface of foam. Since no spines (hind claws that aid in jumping) were added to this Hopper, a smooth surface could create slipping and would not accurately measure the hop distances.

For a crude estimation of the height of the hop, a ruler was set up vertically and initial height value recorded (see Figure 66). Then the Hopper was videotaped hopping in front of the ruler. A maximum height of 2.38 mm was recorded.
Figure 66 – Testing Setup for Vertical and Horizontal Hopping Distances

For an estimation of the range, a ruler was set up horizontally and the start position recorded. Then the Hopper was set through a one-hop sequence and the maximum distance traveled of 25.4 mm was recorded. An average hop recorded was about 12.7 mm out of 15 trials. This then was compared to the Laksonacharoen definition of a good jump. In Section 2 it is stated that Laksonacharoen defines good jumping distance as jump greater than 6 body lengths and poor jumps less than five body lengths. The range value then was compared to this value. It should be noted that since the body of the hopper is .065m in length, a good range is greater than 0.39m. While this value seems impractical, it was an interesting number to note.

In addition, the horizontal hop distance was compared to the values found in Table 15 for a hop range of .095m. The values for the Universal Equations Hop were recalculated using this new average distance. The velocity and acceleration required for hopping is .353 m/s and 1.55 m/s² respectively.

The tests above characterize the Pneumatic Hopper; however, some other more advanced techniques could include an onboard accelerometer to account for all accelerations throughout the hop. Also, a High Speed Video Analysis Setup would be beneficial for exact height and distance values.

Performance approximations for the Pneumatic Hopper were made using both the range and hop height. Using the Universal Motion Equation 2 and the average horizontal range of .0124 m and assuming that the hopper takes off at a 45° angle, a take off velocity was calculated to
be .349 m/s. Also, using equation 3 and the take-off velocity found, an approximate acceleration for the actual Hopper was determined to be 1.519 m/s². These results were then compared the Pneumatic Hopper’s Average Analytical results (see Table 17) and can be seen in Table 21.

Table 21—Built Pneumatic Hopper Motion Comparison with Average Analytical Results

<table>
<thead>
<tr>
<th>Variable at the Moment Before Hop</th>
<th>Actual Hopper Results</th>
<th>Working Model Results</th>
<th>Alexander’s Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Velocity, (m/s)</td>
<td>.349</td>
<td>.251</td>
<td>.194</td>
</tr>
<tr>
<td>% Difference</td>
<td>0</td>
<td>28.2</td>
<td>44.4</td>
</tr>
<tr>
<td>Average Acceleration (m/s²)</td>
<td>1.519</td>
<td>34.52</td>
<td>11.774</td>
</tr>
<tr>
<td>% Difference</td>
<td>0</td>
<td>2143</td>
<td>665.9</td>
</tr>
<tr>
<td>Vertical Hop Height (mm)</td>
<td>2.4</td>
<td>na</td>
<td>.0009</td>
</tr>
<tr>
<td>% Difference</td>
<td>0</td>
<td>na</td>
<td>999.6</td>
</tr>
</tbody>
</table>

Since the Universal Equations were used to find the velocity and acceleration of the actual Hopper, this can account for the discrepancies. As seen previously the Universal Equation Results, it does not predict the acceleration very well, and this is again true. The Working Model and Alexander’s Equation acceleration values are only off by 65.9 percent from each other.

Using the velocity and accelerations approximate values found in the actual Hopper using Universal Equations, the Alexander’s equations were reworked. This resulted in a larger hop height. The new values and the actual hoper values can be seen in Figure 22:

Table 22—Actual and Reworked Alexander’s Equations Results Comparison

<table>
<thead>
<tr>
<th>Variable at the Moment Before Hop</th>
<th>Actual Hopper Results</th>
<th>Reworked Alexander’s Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Velocity, m/s</td>
<td>.349</td>
<td>.494</td>
</tr>
<tr>
<td>% Difference</td>
<td>0</td>
<td>41.5</td>
</tr>
<tr>
<td>Average Acceleration (m/s²)</td>
<td>1.519</td>
<td>10.54</td>
</tr>
<tr>
<td>% Difference</td>
<td>0</td>
<td>585.7</td>
</tr>
<tr>
<td>Vertical Hop Height (mm)</td>
<td>2.4</td>
<td>5.9</td>
</tr>
<tr>
<td>% Difference</td>
<td>0</td>
<td>145.0</td>
</tr>
</tbody>
</table>
The discrepancies in the theoretical and actual Hopper are rather large. This can be accounted for by many factors. Most importantly, no friction was accounted for in all analytical results. In both the pin and slot locations, friction was present in actual practice. Since the force is relatively small, friction plays a large role in the Hopper itself.

Another factor was that the Working Model Results are a computer driven ideal atmosphere where actuators engage instantaneously. Also, full force of the spring was used. This catapulting action is very difficult to duplicate in actual practice. This is the key element that allows the Hopper to achieve high jump heights.

Alexander’s equations rely heavily on the weight and geometry of the Hopper. Also, the equations utilized the velocity and acceleration values that were created by the Working Model Software. This makes them less accurate. In addition, the Universal Motion Equations are inherently a general estimated figure. An onboard accelerometer would be a great tool to measure the actual acceleration of the Hopper throughout hop.

Finally, no lateral movement is accounted for in the moving components. While all components in the analytical models move without slippage or lateral movement, in the actual model this occurs. This lessens the effectiveness of the actuators and thus accounts for the minimized hop height in the actual Hopper.
Section 5  Feasibility of the Designed Pneumatic and EAP Hoppers

The Pneumatic Hopper works well in a controlled laboratory environment. Because of the Hopper's off-board control center and air supply, it is not feasible in actual forest environments. Also, due to the small size of the Hopper, exact fittings for each pneumatic actuator was not possible because of machine tolerances and “big fingers”. However this does achieve a good foundation for grasshopper inspired hoppers. Once optimized and untethered, this could be a capable apparatus in wild fire detection. The durability and powerfulness of the Hopper can be greatly improved by designing a chassis specifically for the pneumatics.

The EAP Hopper has several problems that must be overcome before it is feasible for out-of-laboratory application. Since the Hopper cannot work more than several minutes without hydration, this is a main design focus. An upgrade to create an active hydration system of the EAP Actuator is necessary. Also, to create an un-tethered apparatus, a microcontroller or portable power supply capable of outputting the high current demands of the EAP Actuator must be explored. The overall robustness of the EAP Actuator must be improved as well. A major benefit of the EAP Actuator is the strength that can be seen. For a 5 mm by 20 mm sample an average 26.5 mN force was achieved. This is a strong designing point for the EAP Actuator.

Both Hoppers must consider an enclosed, waterproof, and resilient outside covering before they can be considered to be used in outdoor applications. Also, a recovery program must be created for situations where the hopper has become positioned on its back or side. Overall, further study in this area would be greatly interesting.
Section 6 Recommendations For Future Studies

Electroactive polymers have potentially endless functions besides their current fuel cell and limited biological applications. However, the practical use of this material in laboratory settings needs to be further developed. Since EAP Actuators require such low voltages for actuation, the uses are endless as machines are downsized. While the Hopper is relatively small, it is rather large when working in a MEMS scale. The EAP Actuators would be advantageous in micro-machines because of the small force it exerts and the low activation voltages. Also such devices are often in controlled atmospheres, which would be beneficial because adding a moisture-rich setting could create a longer acting actuator.

In a phone conversation with Matt Bennett, he discussed making a stronger EAP material in the near future. This would elevate some of the force limitations that exist in the EAP Hopper and would be able to produce a greater hopping distance.

Design of a self re-hydrating EAP Actuator would be beneficial to future works. To prevent dehydration the actuator itself could be encased in a fluidic sac or the entire system could somehow maintain moisture. Also a linear acting electroactive polymer or IMPC would also be an interesting advancement to the Hopper and would provide a more direct force as opposed to the bending actuator utilize here.

More experimentation for the EAP Actuator must be conducted. The use of a laser vibration meter and high frequency data acquisition software could be beneficial. The more precise data acquisition instrument could better articulate the current draw and capacitance levels of the EAP Actuator. The laser vibration meter would give us a better understanding of the EAP Actuator throughout a full range of motion.

More experimentation with Shape Memory Alloy Actuators and McKibben Muscle Actuator could also be interesting. Perhaps the long recovery time could be minimized by using two opposing SMA Actuators. Since the voltage still remains low, integration with the Basic Stamp II might be a powerful combination. The strength of the McKibben would be
beneficial to the strength of the Hopper. However, because of the tethered nature of the actuator and onboard air supply would be required.

As with any hopping device, the design and weight of the apparatus can always be streamlined and improved. A thinner, lighter weight carbon fiber could make a difference as well as streamlining the legs to eliminate all extra mass. This would reduce the amount of mass required for the actuator to move.

Another modification to the Hopper design would be to change the material of the chassis. To minimize the current traveling though the body of the Hopper, in future studies a non-conductive plastic should be used for either connection tabs or the entire Hopper. Fiberglass was chosen for its lightweight properties, however a plastic may be a less conductive material. Any additional weight can be eliminated with relief holes throughout. This would isolate each leg and ground the Hopper.

Since the spines--hind claws on the grasshopper--are critical for direction and distance of hopping in actual grasshoppers, it would be interesting to explore the effects of spines on the Robotic Hopper. No claws were added to the Hopper and it was tested on a relatively rough surface. Since grasshoppers that lose their grip on slippery surfaces do not hop as well, it would be interesting to create a hopper that can hop on smooth surfaces.
Definitions

1. **Bending EAP** - polymers that respond with bending, which may be the result of use of multiple layers as bimorph or inherent properties.

2. **Electrostriction** - the non-linear reaction of ferroelectric EAP relating strain to energy squared. (Bar-Cohen, website).

3. **Electroactive Polymer (EAP)** - general term describing polymers that respond to electrical stimulation.

4. **Electronic EAP** - polymers that change shape or dimensions due to migration of electrons in response to electric field, usually in a dry environment.

5. **Ionic EAP** - polymers that change shape or dimensions due to migration of ions in response to an electric field, usually wet and contains electrolytes.

6. **Longitudinal EAP** - polymers that respond with change in length.

7. **Piezoeactuator (PZT)** - Plumbum (lead) Zirconate Titanate. Polycrystalline ceramic material with piezoelectric properties.

8. **Shape Memory Alloy** - Shape Memory Alloys (SMAs) are metal alloys that can recover apparent permanent strains when they are heated above a certain temperature.

9. **Smart Material** – An all-inclusive term describing any material that responds with a change in shape upon application of externally applied driving forces.

10. **Piezoelectric Polyvinylidene Floride (PVDF)** - Polymeric materials which are disclosed as being either inherently piezoelectric or have been treated (via polarizing) to give them usable piezoelectric properties (for example, PVDF, Mylar, frozen rubber, PVC, etc.).
References


[12] HyperPhysics website: http://hyperphysics.phystr.gsu.edu/hbase/electric/pplate.html#c2


[26] SMC Website: www.smcusa.com


Appendix A: Computer Simulations

EAP Hopper MatLab Code:

File NewNumbers.m

% C BIEMEIER 11/01/02
% GRASSHOPPER INSPIRED ROBOTIC HOPPER THESIS
% UNITS IN METERS

clc
clf
clear

% working Model INPUT*****************************************
% phase 1
matrix1 = xlsread('datagood.xls');
timecl=matrix1(1:164,1);
position=matrix1(1:164,2);
velocity1=matrix1(1:164,3);
acceleration1=matrix1(1:164,4);
xpos=matrix1(1:164,5);
xvel=matrix1(1:164,6);
xaccel=matrix1(1:164,7);
xposnew=matrix1(1:164,8);

% phase 2

timec2=matrix1(164:189,1);
position2=matrix1(164:189,2);
velocity2=matrix1(164:189,3);
acceleration2=matrix1(164:189,4);
xpos2=matrix1(164:189,5);
xvel2=matrix1(164:189,6);
xaccel2=matrix1(164:189,7);
xposnew2=matrix1(164:189,8);

% phase 3

timec3=matrix1(189:337,1);
position3=matrix1(189:337,2);
velocity3=matrix1(189:337,3);
acceleration3=matrix1(189:337,4);
xpos3=matrix1(189:337,5);
xvel3=matrix1(189:337,6);
xaccel3=matrix1(189:337,7);
xposnew3=matrix1(189:337,8);

% ASSUMPTIONS**********************************************
l=.02; % length from pin to center of gravity
L1=-.09;
L2=.012;
L3=.003;
L4=.011;
h=.05;
b=.02;
g=9.81;

C. Bielmeier
Appendix A: Computer Simulations

m = 0.33 * 10^-3; % mass in Kg
w = m * g; % weight of leg in grams
F1 = 0.002; % extensor force in N
F2 = 0.002; % flexor force in N

\( \phi = \text{position}(1,1); \) % leg angle in radians
\( x_0 = \text{xposnew}(1,1); \)
K = 3; % spring force in N/m
l = (h^2 + b^2) * (m/12);

% Phase 1

\( t_1 = [0:0.001:0.13]; \)
\( t_1 \text{sub1} = [0:0.001:0.077]; \)

sim ('NewSimPhase1')

\( \phi a = \text{theta1}(78,1); \)
\( \phi aa = \text{theta1dot}(78,1); \)
\( x_0a = \text{x1t}(78,1); \)
\( x_0aa = \text{x1t}(78,1); \)

sim ('NewSimPhase1 time2')

% Phase 2

L5 = 0.002;
L6 = 0.017;
L7 = 0.003;
L8 = 0.004;

\( \phi 2 = \text{position2}(1,1); \) % leg angle in radians
\( \phi 2 \text{dot} = \text{velocity2}(1,1); \)
\( x_{02} = \text{xposnew2}(1,1); \)
\( x_{2dot} = \text{xvel2}(1,1); \)

sim ('NewSimPhase2')

C. Bielmeier
Appendix A: Computer Simulations

plot(timec2,position2,'b',time2,theta2,'r');
legend('Working Model','Lumped Mass Simulink');grid;
AXIS([.13 .15 .25 .15])
title('EAP Hopper Phase 2: Phi Position Comparision');
xlabel('Time (sec)');
ylabel('Phi (radians)');

figure (4);
plot(timec2,xposnew2,'b',time2,x2t,'r');
legend('Working Model','Lumped Mass Simulink');grid;
AXIS([.13 .15 .04 .043])
title('EAP Hopper Phase 2: X Displacement Comparision');
xlabel('Time (sec)');
ylabel('Displacement (meters)');

% **************************************************************
% Phase 3 **********************************************************

phi3=position3(1,1); %leg angle in radians
phi3dot=velocity3(1,1);
x03=xposnew3(1,1);
x3dot=xvel3(1,1);
sim ('NewSimPhase3')

figure (5);
plot(timec3,position3,'b',time3,theta3,'r');
legend('Working Model','Lumped Mass Simulink');grid;
AXIS([.15 .35 .15 .15])
title('EAP Hopper Phase 3: Phi Position Comparision');
xlabel('Time (sec)');
ylabel('Phi (radians)');

figure (6);
plot(timec3,xposnew3,'b',time3,x3t,'r');
legend('Working Model','Lumped Mass Simulink');grid;
AXIS([.15 .35 .04 .046])
title('EAP Hopper Phase 3: X Displacement Comparision');
xlabel('Time (sec)');
ylabel('Displacement (meters)');

%COMPARISION FOR 3 PHASES***************************************

allphasetheta=[theta1; theta1a;theta2; theta3];
allphasetime=[time;timea;time2;time3];
allphasex=[x1;x1a;x2;x3t];
allphasethetadot=[theta1dot; theta1dota;theta2dot; theta3dot];
allphasethetadotdot=[theta1dotdot; theta1dotdot;theta2dotdot; theta3dotdot];
WMtime=[timecl;timec2;timec3];
WMtheta=[position;position2;position3];
WMx=[xposnew;xposnew2;xposnew3];
WMvel=[velocity1;velocity2;velocity3];
WMaccel=[acceleration1;acceleration2;acceleration3];

C. Bielmeier
Appendix A: Computer Simulations

```matlab
figure (7)
plot(WMtime,WMtheta,'b',alphasetime,alphatheta,'r');
legend('Working Model','Lumped Mass Simulink');grid;
title('EAP Hopper Phi Position Comparision for All Three Phases');
xlabel('Time (sec)');
ylabel('Phi (radians)');

figure (8)
plot(WMtime,WMx,'b',alphasetime,alphax,'r');
legend('Working Model','Lumped Mass Simulink');
AXIS([0 .35 .040 .046])
title('EAP Hopper X Displacement Comparision for All Three Phases');
xlabel('Time (sec)');
ylabel('Displacement (meters)');
```
Appendix A: Computer Simulations

Pneumatic Hopper MatLab Code:

File: PnewNumbers.m

% C BIEMEIER  11/01/02
% GRASSHOPPER INSPIRED ROBOTIC HOPPER THESIS
% UNITS IN METERS
% Pneumatic Hopper

clc
clf
clear

% working Model INPUT****************************************************
% phase 1
matrix1 = xlsread('pneugooddata.xls');
timec1=matrix1(1:25,1);
position=matrix1(1:25,2);
velocity1=matrix1(1:25,3);
acceleration1=matrix1(1:25,4);
xpos=matrix1(1:25,5);
xvel=matrix1(1:25,6);
xaccel=matrix1(1:25,7);
xposnew=matrix1(1:25,8);

% phase 2
timec2=matrix1(25:33,1);
position2=matrix1(25:33,2);
velocity2=matrix1(25:33,3);
acceleration2=matrix1(25:33,4);
xpos2=matrix1(25:33,5);
xvel2=matrix1(25:33,6);
xaccel2=matrix1(25:33,7);
xposnew2=matrix1(25:33,8);

% phase 3
timec3=matrix1(33:172,1);
position3=matrix1(33:172,2);
velocity3=matrix1(33:172,3);
acceleration3=matrix1(33:172,4);
xpos3=matrix1(33:172,5);
xvel3=matrix1(33:172,6);
xaccel3=matrix1(33:172,7);
xposnew3=matrix1(33:172,8);

% ASSUMPTIONS***************************************************************************
l=.02;  % length from pin to center of gravity
L1=-.09;
L2=.012;
L3=.003;
L4=.011;
h=.05;
b=.02;
Appendix A: Computer Simulations

g=9.81;
m=.0411; % mass in Kg
w=m*g; % weight of leg in grams
F1=3.47; % extensor force in N
F2=3.47; % flexor force in N

phi=position(1,1); % leg angle in radians
x0=xposnew(1,1);
K=10; % spring force in N/m
lcg=(h^2+b^2)*(m/12);
l=lcg+m*l^2;

% ****************************
% Phase 1
% ****************************
sim ('pNewSimPhase1')

phia=theta1(81,1);
phiaa=theta1dot(81,1);
x0a=x1t(81,1);
x0aa=x1tdota(81,1);

sim('pNewSimPhase1time2')

figure (1);
plot(time1,position,'b',time,theta1,'r',timea,theta1a,'r');
legend('Working Model','Lumped Mass Simulink');grid;
title('Pneumatic Hopper Phase1: Phi Position Comparision');
xlabel('Time (sec)');
ylabel('Phi (radians)');

figure (2);
plot(time1,xposnew,'b',time,x1t,'r',timea,x1ta,'r');
legend('Working Model','Lumped Mass Simulink');
axis([0 .01 .039 .045])
title('Pneumatic Hopper Phase1: X Displacement Comparision');
xlabel('Time (sec)');
ylabel('Displacement (meters)');

% ****************************
% Phase 2
% ****************************

L5=.002;
L6=.017;
L7=.003;
L8=.004;

phi2=theta1a(21,1); % leg angle in radians
phi2dot=theta1dota(21,1);
x02=x1ta(21,1);
x2dot=x1tdota(21,1);
sim ('pNewSimPhase2')

% ****************************
figure (3);
plot(time2,position2,'b',time2,theta2,'r');
legend('Working Model','Lumped Mass Simulink');grid;
Appendix A: Computer Simulations

AXIS([.01 .013 -1.5 -.8])
title('Pneumatic Hopper Phase 2: Phi Position Comparision');
xlabel('Time (sec)');
ylabel('Phi (radians)');

figure (4);
plot(timec2,xposnew2,'b',time2,x2t,'r');
legend('Working Model','Lumped Mass Simulink');
AXIS([.01 .013 .039 .045])
title('Pneumatic Hopper Phase 2: X Displacement Comparision');
xlabel('Time (sec)');
ylabel('Displacement (meters)');

% PHASE 3

phi3=theta2(31,1); % leg angle in radians
phi3dot=velocity3(31,1);
x03=xposnew3(31,1);
x3dot=xvel3(31,1);
sim ('PNewSimPhase3')

figure (5);
plot(timec3,position3,'b',time3,theta3,'r');
legend('Working Model','Lumped Mass Simulink');grid;
AXIS([.013 .035 -1.5 .7])
title('Pneumatic Hopper Phase 3: Phi Position Comparision');
xlabel('Time (sec)');
ylabel('Phi (radians)');

figure (6);
plot(timec3,xposnew3,'b',time3,x3t,'r');
legend('Working Model','Lumped Mass Simulink');
AXIS([.013 .035 .038 .043])
title('Pneumatic Hopper Phase 3: X Displacement Comparision');
xlabel('Time (sec)');
ylabel('Displacement (meters)');

% COMPARISION FOR 3 PHASES

allphasetheta=[theta1; theta1a; theta2; theta3];
allphasetime=[time;timea;time2;time3];
allphasex=[x1;x1a;x2;x3t];
allphasethetadot=[theta1dot;theta1dota;theta2dot;theta3dot];
allphasethetadotdot=[theta1dotdot;theta1dotdota;theta2dotdot;theta3dotdot];

WMtime=[timec1;timec2;timec3];
WMtheta=[position;position2;position3];
WMx=[xposnew;xposnew2;xposnew3];
WMVelocity=[velocity1;velocity2;velocity3];
WMaccel=[acceleration1;acceleration2;acceleration3];

figure (7)
Appendix A: Computer Simulations

plot(WMtime,WMtheta,'b',allphasetime,allphasetheta,'r');
legend('Working Model','Lumped Mass Simulink');grid;
AXIS([0 .035 -1.4 .7])
title('Pneumatic Hopper Phi Position Comparision for All Three Phases');
xlabel('Time (sec)');
ylabel('Phi (radians)');

figure (8)
plot(WMtime,WMx,'b',allphasetime,allphasex,'r');
legend('Working Model','Lumped Mass Simulink');
AXIS([0 .035 .038 .045])
title('Pneumatic Hopper X Displacement Comparision for All Three Phases');
xlabel('Time (sec)');
ylabel('Displacement (meters)');

figure (9);
plot(WMtime,WMaccel,'b',allphasetime,allphasethetadotdot,'r');
title('Acceleration of Lower Leg Over Time for Working Model and Lumped Sum Equations');
legend('Working Model Results','Lumped Sum Equations');
AXIS([0 .035 -25000 25000]);
xlabel ('Time (sec)');
ylabel('Acceleration(radians/s^2)')

figure (10);
plot(WMtime,WMVelocity,'b',allphasetime,allphasethetadot,'r');
title('Velocity of Lower Leg Over Time for Working Model and Lumped Sum Equations');
legend('Working Model Results','Lumped Sum Equations');
AXIS([0 .035 -150 100]);
xlabel ('Time (sec)');
ylabel('Acceleration(radians/s)')
Appendix A: Computer Simulations

Current Test MatLab Code:

File: test.m

```matlab
% CBIELMEIER HOPPER THESIS
% CURRENT VOLTAGE PLOT
clc
clf
clear

matrix1 = xlsread('GoodTrials.xls');
time=matrix1(:,1);
d310=matrix1(:,2);fin310=time(34);bf310=matrix1(:,10);
d32=matrix1(:,3);fin32=time(34);bf32=matrix1(:,11);
d311=matrix1(:,4);fin311=time(41);bf311=matrix1(:,12);
d51=matrix1(:,5);fin51=time(38);bf51=matrix1(:,13);
d42=matrix1(:,6);fin42=time(40);bf42=matrix1(:,14);
d36=matrix1(:,7);fin36=time(32);bf36=matrix1(:,15);
d52=matrix1(:,8);fin52=time(58);bf52=matrix1(:,16);
d39=matrix1(:,9);fin39=time(34);bf39=matrix1(:,17);

%CONSTANTS
A=4;
C=1.58*10^-6;
R1R2=zeros(2,8);

% 3.10 ******************************************************
R1=.025;
R2=.009;
R1R2(1,1)=R1;
R1R2(2,1)=R2;
T1T2ratio310=(R2*(R1+R2))/(R1*R2)
iss310=A/(R1+R2)
num=[(A/R1) A/(R1*R2*C)];
den=[1 (R1+R2)/(R1*R2*C)];
sys310=tf(num,den);
y310=step(sys310);
[M,N]= size(y310)
incr=(fin310/(M-1));
time310=[0:incr:fin310];
figure (1);
plot(time,d310,'b', time310, y310,'r', time, bf310,'m');
legend('Data','Equation','Excel Best Fit');
AXIS([0 7 0 180]);
title('Comparison Of Current Circuit and Lab Data for Trial 3.10');
xlabel ('Time(sec)');
ylabel('Current (mAmps)');
Appendix A: Computer Simulations

% 3.2 *******************************************************
R1=.030;
R2=.017;
R1R2(1,2)=R1;
R1R2(2,2)=R2;
T1T2ratio32=(R2*(R1+R2))/(R1*R2)
iss32=A/(R1+R2)
num=[(A/R1) A/(R1*R2*C)];
den=[1 (R1+R2)/(R1*R2*C)];
sys32=tf(num,den);
y32=step(sys32);
[M,N]= size(y32)
incr=(fin32/(M-1));
time32=[0:incr:fin32];
figure (2);
plot(time,d32,'b',time32,y32,:r,
time,bf32,'m');
legend('Data','Equation','Excel Best Fit');
AXIS([0 7 0 180]);
title('Comparison Of Current Circuit and Lab Data for Trial 3.2');
xlabel ('Time(sec)');
ylabel('Current (mAmps)');

% 3.11 *******************************************************
R1=.026;
R2=.026;
R1R2(1,3)=R1;
R1R2(2,3)=R2;
T1T2ratio311=(R2*(R1+R2))/(R1*R2)
iss311=A/(R1+R2)
num=[(A/R1) A/(R1*R2*C)];
den=[1 (R1+R2)/(R1*R2*C)];
sys311=tf(num,den);
y311=step(sys311);
[M,N]= size(y311)
incr=(fin311/(M-1));
time311=[0:incr:fin311];
figure (3);
plot(time,d311,'b',time311,y311,:r,
time,bf311,'m');
legend('Data','Equation','Excel Best Fit');
AXIS([0 7 0 180]);
title('Comparison Of Current Circuit and Lab Data for Trial 3.11');
xlabel ('Time(sec)');
ylabel('Current (mAmps)');

% 5.11 *******************************************************
R1=.028;
R2=.029;
R1R2(1,4)=R1;
R1R2(2,4)=R2;
T1T2ratio511=(R2*(R1+R2))/(R1*R2)
iss511=A/(R1+R2)
num=[(A/R1) A/(R1*R2*C)];
den=[1 (R1+R2)/(R1*R2*C)];
Appendix A: Computer Simulations

sys511=tf(num,den);
y511=step(sys511);
[M,N]= size(y511)
incr=(fin511/(M-1));
time511=[0:incr:fin511]';

figure (4);
plot(time,d511,'b',time511,y511,'r', time, bf511,'m');
legend('Data','Equation','Excel Best Fit');
AXIS([0 7 0 180]);
title('Comparison Of Current Circuit and Lab Data for Trial 5.11');
xlabel ('Time(sec)');
ylabel('Current (mAmps)');

% 4.2 ****************************
R1=.034;
R2=.040;
R1R2(1,5)=R1;
R1R2(2,5)=R2;
T1T2ratio42=(R2*(R1+R2))/(R1*R2)
iss42=A/(R1+R2)
num=[(A/R1) A/(R1*R2*C)];
den=[1 (R1+R2)/(R1*R2*C)];
sys42=tf(num,den);
y42=step(sys42);
[M,N]= size(y42)
incr=(fin42/(M-1));
time42=[0:incr:fin42]';
figure (5);
plot(time,d42,'b',time42,y42,'r', time, bf42,'m');
legend('Data','Equation','Excel Best Fit');
AXIS([0 7 0 180]);
title('Comparison Of Current Circuit and Lab Data for Trial 4.2');
xlabel ('Time(sec)');
ylabel('Current (mAmps)');

% 3.6 ****************************
R1=.037;
R2=.029;
R1R2(1,6)=R1;
R1R2(2,6)=R2;
T1T2ratio36=(R2*(R1+R2))/(R1*R2)
iss36=A/(R1+R2)
num=[(A/R1) A/(R1*R2*C)];
den=[1 (R1+R2)/(R1*R2*C)];
sys36=tf(num,den);
y36=step(sys36);
[M,N]= size(y36)
incr=(fin36/(M-1));
time36=[0:incr:fin36]';
figure (6);
plot(time,d36,'b',time36,y36,'r', time, bf36,'m');
legend('Data','Equation','Excel Best Fit');
AXIS([0 7 0 180]);
Appendix A: Computer Simulations

title('Comparison Of Current Circuit and Lab Data for Trial 3.6');
xlabel('Time (sec)');
ylabel('Current (mAmps)');

% 5.2 ******************************************************************************
R1=.035;
R2=.055;
R1R2(1,7)=R1;
R1R2(2,7)=R2;
T1T2ratio52=(R2*(R1+R2))/(R1*R2)
iss52=A/(R1+R2)
um=[(A/R1) A/(R1*R2*C)];
den=[1 (R1+R2)/(R1*R2*C)];
sys52=tf(num,den);
y52=step(sys52);
[M,N]= size(y52);
incr=(fin52/(M-1));
time52=[0:incr:fin52];
figure(7);
plot(time,d52,'b',time52,y52,':r',time,bf52,'m');
legend('Data','Equation','Excel Best Fit');
AXIS([0 7 0 180]);
title('Comparison Of Current Circuit and Lab Data for Trial 5.2');
xlabel('Time (sec)');
ylabel('Current (mAmps)');

% 3.9 ******************************************************************************
R1=.058;
R2=.077;
R1R2(1,8)=R1;
R1R2(2,8)=R2;
T1T2ratio39=(R2*(R1+R2))/(R1*R2)
iss39=A/(R1+R2)
um=[(A/R1) A/(R1*R2*C)];
den=[1 (R1+R2)/(R1*R2*C)];
sys39=tf(num,den);
y39=step(sys39);
[M,N]= size(y39);
incr=(fin39/(M-1));
time39=[0:incr:fin39];
figure(8);
plot(time,d39,'b',time39,y39,':r',time,bf39,'m');
legend('Data','Equation','Excel Best Fit');
AXIS([0 7 0 180]);
title('Comparison Of Current Circuit and Lab Data for Trial 3.9');
xlabel('Time (sec)');
ylabel('Current (mAmps)');

%COMPARISON DATA ******************************************************************************
allSS=[iss310;iss32;iss311;iss511;iss42;iss36;iss52;iss39]
allT1T2ratio=[T1T2ratio310;T1T2ratio32;T1T2ratio311;T1T2ratio511;T1T2ratio42;T1T2ratio36;T1T2ratio52;T1T2ratio39]
Appendix A: Computer Simulations

R1R2
r1r2=zeros(1,8);
r1r2(1)=R1R2(1,1)/R1R2(2,1);
r1r2(2)=R1R2(1,2)/R1R2(2,2);
r1r2(3)=R1R2(1,3)/R1R2(2,3);
r1r2(4)=R1R2(1,4)/R1R2(2,4);
r1r2(5)=R1R2(1,5)/R1R2(2,5);
r1r2(6)=R1R2(1,6)/R1R2(2,6);
r1r2(7)=R1R2(1,7)/R1R2(2,7);
r1r2(8)=R1R2(1,8)/R1R2(2,8);
r1r2
figure (9);
plot(time,bf310,'b',time,bf311,'r',time,bf311,'g',time,bf311,'c',time,bf36,'m',time,bf52,'y',time,bf39,'xb',time310,y310,':b',time32,y32,':r',time311,y311,':g',time511,y511,':c',time42,y42,':m',time36,y36,':k',time52,y52,':y',time39,y39,':-b');
legend('3.10','3.2','3.11','5.11','4.2','3.6','5.2','3.9');
title('Comparison of Excel Best Fit and Circuit Diagram Equations');
xlabel('Time (sec)');
ylabel('Current (mAmgs)');
Appendix A: Computer Simulations

1. Phase 1: Simulink Model for Alpha Greater Than Phi
Appendix A: Computer Simulations

Phase 1: Simulink Model for Alpha Less Than Phi
Appendix A: Computer Simulations

2. Phase 2: Simulink Model
Appendix A: Computer Simulations

Phase 2: Simulink Model con't
Appendix A: Computer Simulations

3. Phase 3: Simulink Model
Appendix B: Hopper Documentation

Component Drawings

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Basic Stamp Wiring Schematics and Programming Code

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g. Basic Stamp II Code

'${STAMP BS2}
PNEUMATIC HOPPER STAMP CODE FOR ONE LEG 
'C BIELMEIER DEC 10

KICK:
HIGH 0 'FLEXOR MUSCLE
PAUSE 1000
HIGH 1 'EXTENSOR MUSCLE
PAUSE 1000
LOW 0 'LEFT ACTIVATE TO COMPRESS SPRING
PAUSE 1000
LOW 1 'LEFT EXTENSOR MUSCLE ACTIVATE
PAUSE 2000
GOTO KICK
Appendix C: Current Tests For Wet and Dry Setups

Wet Test Setup Using 4 Volt Input

Wet Test Setup Using 3.5 Volt Input
Appendix C: Current Tests For Wet and Dry Setups

Dry Test Setup Using 4 Volt Input

- trial 2
- trial 1
Appendix D: Lumped Mass Equation Approximations

The Lumped Mass Equations used in this paper are approximations of the real model for simplicity. Due to the complex nature of the actual configuration, some variables were assumed to be negligible. The following diagram is the complete Lumped Mass Approximation. In this figure all the red colored items are not applied in the Lumped Mass Equations. Please note that $F_s$ is equal to the slot reaction force.

Now considering Phase One when only $F_1$ is active and $F_2$ is zero. Using this Figure and taking the moments about point $O$, the following equations can be found:
Appendix D: Lumped Mass Equation Approximations

\[ I\alpha + m\ddot{y} + m\ddot{b} = \sum M_o = -wl \sin \phi + F_i \sin(\alpha - \phi)L2 + F_i \cos(\alpha - \phi)L1 \] (1)

where:

\[ a = l \sin \phi \] (2)

\[ b = l \cos \phi \] (3)

\[ \sum F_x = m\ddot{x} = -kx_o + F_1 \cos(\alpha_i) \] (4)

where

\[ x_o = x - l \sin \phi \] (5)

Looking at these equations, the phi equation 1 becomes much more complicated as compared to equation 22. When leaving out the extra inertia terms, the equations yield an approximate solution to this model. In Equation 21, 25, and 27 the inertia terms \( m\ddot{y} + m\ddot{b} \) were ignored. In equations 22, 26, and 28 note that the inertia term \( m\ddot{X}_{mc} \) for the mass center was approximated by \( m\ddot{X} \) where X is the pin position.