Force Measurement of Basilisk Lizard Running on Water

by

Andrew Sweeney

A Thesis Presented in Partial Fulfillment
of the Requirement for the Degree
Master of Science

Approved April 2019 by the
Graduate Supervisory Committee:

Hamidreza Marvi, Chair
David Lentink
Hyunglae Lee

ARIZONA STATE UNIVERSITY

May 2019

ABSTRACT

Basilisk lizards are often studied for their unique ability to run across the surface of water. Due to the complicated fluid dynamics of this process, the forces applied on the water's surface cannot be measured using traditional methods. This thesis presents a novel technique of measuring the forces using a fluid dynamic force platform (FDFP), a light, rigid box immersed in water. This platform, along with a motion capture system, can be used to characterize the kinematics and dynamics of a basilisk lizard running on water. This could ultimately lead to robots that can run on water in a similar manner.

This research was supported by the Fulton Masters Opportunity for Research in Engineering. It also would not have been possible without resources and support from the Bio-Inspired Robotics Technology and Healthcare Lab.

TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

Chapter 1

INTRODUCTION

1.1 Motivation and Overview

The basilisk lizard has become a species of interest in the bio-inspired robotics community in recent years. Through its evolution, it developed extraordinary movement capabilities that enable it to escape predators on many different types of terrain. It excels in moving on and between solid terrain and dry and wet granular media [1]. Additionally, the basilisk lizard is unique among vertebrates for its ability to run across the surface of a body of water. As a damping surface, water exaggerates the effects of size on motion [2]. While some insects can run on water using surface tension [3], this method is impossible for animals of significant mass. The basilisk lizard remains above the surface using a different method. As its hind foot penetrates the water's surface, it creates an air-filled cavity. It then retracts its foot before the cavity closes, thus minimizing its contact with the water. This mechanism significantly reduces drag as it propels itself across the water at a speed of approximately 1.6 m/s [4]. The lizard's ability to run effectively on both land and water would be a highly desirable skill to emulate in robots [5, 6]. Figure 1.1 below shows a running lizard at different points in its stride.

Figure 1.1: The Stride of a Basilisk Lizard Running on Water

Direct calculation of the force interactions of water running is generally impractical because it requires precise knowledge of the fluid velocity and pressure fields [4, 7]. In the past, the lizard's force interactions with the water have been approximated using particle image velocimetry (PIV). This technique uses cameras to continuously record the position of visible particles that have been placed in the fluid, calculating a vector field. This is then integrated to form a pressure field. However, this technique has many sources of error, including system noise, camera resolution deficiency, and complexities in turbulence measurement [8].

A novel method of calculating the lizard's kinematics has been derived from recent research using an aerodynamic force platform (AFP) to measure the force interactions of birds during flight in a direct and non-intrusive way. The AFP was mounted on three statically determinate Nano43 sensors (six-axis, SI-9-9.125 calibration; ATI Industrial Automation) sampling at 1000 Hz with a resolution of 2 mN. By integrating the pressure fields along the surfaces of the enclosure using simplified versions of the Navier-Stokes equations, the forces generated by the bird during takeoff and landing were determined. This resulted in graphs of the horizontal and vertical forces vs. time [9].

The goal of this project has been to implement a similar method of measuring the force interactions of basilisk lizards using a fluid dynamic force platform (FDFP). Much like flying animals, swimming animals move via the force interaction with a fluid generated by their driving stroke [4]. Applying Newton's third law to the incompressible fluid shows that the net upward force at the interface between the animal and the fluid must have an equal and opposite force distributed across the fluid's boundary [10]. The air pressure around the lizard is effectively constant, which means that only the pressure fields of the water need to be recorded [11]. For this reason, an open-topped box mounted on three sensors has been built instead of a full enclosure. By filling the box with water and submerging it in a larger container of water, it can be made neutrally buoyant. Pressure calculations are based on velocity, so this buoyancy will not affect the fluid forces [11]. The highly precise sensors can then detect the impulses of the lizard as it runs across the surface of the water in the box.

There are several assumptions that simplify the Navier-Stokes equations for water running. It is assumed that the shear stress on the air side of the liquid-gas interface is negligible, and that there is no flow through the interface. The air pressure over the lizard's body is assumed to be constant, as well as the air pressure on the control surface. Furthermore, the surface tension at the liquid-gas interface is negligible. Lastly, the unsteady body force due to the displacement of liquid and gas is considered negligible due to the lizard's relatively small size. Using these assumptions, the equation simplifies to

$$F(t) = -\iint_{CS} p\mathbf{n}dS + \iint_{CS} \overline{\overline{\tau}}\mathbf{n}dS$$

where p is the fluid pressure, $\mathbf{n}$ is the normal vector of the control surface, and $\overline{\overline{\tau}}$ is the shear stress tensor [11]. Using this integral to process data from the experimental setup, the horizontal and vertical forces of the lizard can be calculated with respect to time. By placing markers on the lizard and recording its locomotion using OptiTrack, this data can be synchronized with visual information about the lizard's stride, enabling the calculation of forces and torques about the lizard's joints or center of mass [12].

1.2 Characteristics of the Basilisk Lizard

The basilisk lizard is most commonly found in Tamaulipas and Michoacan in Mexico, and as far south as Ecuador and Colombia. The males are larger than the females, with a large dorsal crest covering the back and part of the tail [13]. They live mainly near small bodies of water such as rivers, lakes, ponds, and streams. This setting provides a variety of media upon which the lizards can effectively move, including wet and dry granular media as well as water [14]. The ability of lizards to move and transition quickly over these terrains is critical for effectively hunting prey, escaping predators, and defending territory [15]. Younger lizards tend to be more concentrated very close to the water, while older lizards spend their time in trees and other foliage nearby. This distinction could be a result of territory protection, with the more powerful older lizards relegating the younger ones away from their preferred locations [16, 17]. Another possible explanation is that the younger, smaller lizards have more aptitude for running on water. One study found that the size of the lizard had no effect on speed, but it did reduce the water running stamina of larger lizards [18].

The genus *basiliscus* contains five species of lizards. Two of them will be the focus of this research: *Basiliscus vittatus*, the brown basilisk, and *basiliscus plumifrons*, the green basilisk.

1.3 Animal Water Running

Through the cycle of natural selection, biological systems have spent countless iterations developing extraordinary mobility-related survival techniques. In the scientific community, the benefit of studying these techniques is well understood. Many mechanical systems have been proposed and developed as a direct result of biological inspiration [19]. By understanding the underlying principles of biological locomotion, we can understand and emulate these highly refined processes.

Water running can be separated into two broad categories based on the ratio of the animal's body weight to its maximum curvature force:

$$M_c = \frac{Mg}{\sigma P}$$

where M is the mass, g is the acceleration due to gravity, σ is the surface tension, and P is the contact perimeter. Water runners with $M_c < 1$ tend to be small invertebrates, such as the family of insects known as water striders (Gerridae). Due to their high ratio of surface area to body mass, water striders are able to remain on top of a body of water without breaking its surface tension. They can then use their legs to propel themselves forward [20].

Animals with $M_c > 1$ use the second type of water running, which is an exceptionally rare skill in nature. It applies to any animal that attempts to water run while breaking the surface tension of the water. Unlike the water strider's technique, the effectiveness of this method is contingent upon constant movement; a basilisk lizard will sink if it is not actively running [21]. While certain species of bird and lizard can perform this technique with limited success, only the basilisk lizard can make extensive use of this method throughout its entire life cycle.

1.4 Physics of Water Running

There are two basic functions of a water runner's stride: keeping its body above the water, and propelling it forward [16]. A single footstep of the basilisk has been categorized into four distinct phases: slap, stroke, recovery up, and recovery down. For the lizard to be supported, the sum of the upward impulses during one stride must be at least equal to the downward impulse due to gravity [22]. These impulses are generated during the first two stride phases. The slap phase marks the initial impact of the foot upon the surface of the water. It is characterized by a high peak of pressure at the fluid-body interface [23]. During the stroke phase, the contact pressure between the foot and the water decreases. The stroke is a longer phase than the slap, however, resulting in a greater total contribution to the impulse. As the foot transitions from slap to stroke, its angle with respect to the water increases. Thus, the slap generates primarily medial forces, helping with the first basic function of keeping the lizard supported. In contrast, the stroke generates primarily lateral forces, helping with the second basic function of propelling the lizard forward [24].

The recovery up phase is comprised of the lizard retracting its foot from below the water's surface. One of the primary reasons that basilisk lizards are adept at water running is that they create a "pocket" of air in the water above their foot during the stroke phase. Their stride is timed such that during the recovery up phase, the lizard's foot is completely out of the water before this pocket of air closes [25]. This method of running greatly reduces the lizard's drag, enabling it to run at relatively high speeds despite its breaking of surface tension. The time that it takes for the pocket of air to close is given by the equation:

$$2.285(r_{eff}/g)^{0.5}$$

Where g denotes gravity and r_{eff} denotes the effective radius of the lizard's foot. Finally, during recovery down, the lizard increases the velocity of its foot in preparation for the next slap. The foot does not experience any significant external forces during either of the recovery phases [26].

The length of the lizard's stride is typically calculated based on where it places its feet during the slap phase. This length has two contributing factors. The first is the limb length; longer limbs will result in a longer stride. The second is the distance that the hipbone sockets, or acetabula, move during the time that the feet are not in the water. The contribution of this second factor increases during water running, with the lizard lengthening its stride significantly by rotating its pelvis to move the acetabulum forward on the side that is in the recovery phases [16].

The functionality of the basilisk lizard's tail is often neglected in locomotion studies, perhaps partially because it is not fully understood. The tail's movement during water running is much the same as its movement during bipedal land running. In order to better understand its effects, one research group removed part of the tail before prompting the lizards to run [16]. It was found that the lizards could no longer run bipedally. The tail makes up approximately 18% of the lizard's total body mass [4], enabling it to function as a counterweight for the lizard's head and trunk. This keeps the lizard's center of mass in a region of stability above its legs, enabling static locomotion. This is especially critical when running on a highly yielding surface, which is more conducive to tripping and falling [24]. Additionally, the lizard runs with its tail submerged, which results in frictional drag from the water that helps it maintain an upright posture [4]. Removing part of the tail caused the center of mass to be in front of the legs, creating an unbalanced moment during bipedal strides and causing the lizards to fall forward [16].

Another morphological trait of basilisk lizards that aids in water running is their toe fringes. These fringes are comprised of scales that extend off the skin of the toe to form a sort of flap. The fringes increase the surface area of the foot, resulting in larger impulses during the slap and stroke phases. One study surgically removed the toe fringes of a group of basilisk lizards. It was found that all lizards were still able to run on water, but they sank lower into the water due to the reduced impulse. This effect was especially pronounced in older, heavier lizards. It was therefore concluded that the fringes are not essential for water running, but they do improve the lizard's ability to do so [16].

1.5 Robotic Water Running

The surface tension method of water running has been successfully implemented in a robotic system [27]. The miniature "water strider robot" was able to travel across water at a speed of 2.3 cm/s [3]. To the best of our knowledge, however, no robot has yet been developed that can run across water as basilisk lizards do. There are many challenges associated with such an undertaking. One is the impulse requirements. In order to remain afloat, the combined impulse generated by the robot's slap and stroke must be equal to or greater the downward impulse due to gravity. In other words,

$$I_{slap} + I_{stroke} \geq mgT_{stride}$$

At a minimum, the stride frequency must be high enough to avoid excess drag during the recovery phase as the basilisk lizard does. Increasing the frequency further can increase the vertical force generated and the robot's speed [28], but this also requires a greater power input. If the robot is connected to an external power source, its mobility and applications will be limited, and the weight of the wiring will affect its speed and balance. If it is battery-powered, however, the life of the battery will face limitations. Increasing the size of the battery also increases the mass of the robot, which contributes to the problem by increasing the required impulse. Additionally, due to splashing and the potential for malfunctions, the entire robot is liable to get wet. Therefore, for safety purposes and the prevention of electrical shorts, all components of the robot must be waterproof [29]. This also adds weight, since all of the electrical components require protection. Lastly, there is the issue of balance. The basilisk lizard makes this issue look deceptively easy; in reality, it is exceptionally difficult to maintain a net moment of zero around a body's center of mass while that body is running across water. The main concerns are pitch and roll [30]; yaw is less likely to lead to the robot capsizing.

One robot was designed to imitate the lizard's stride. It was supported by a load cell to measure the upward force of its strokes on water. The researchers designed several different types of feet to imitate different aspects of a basilisk lizard's foot. For example, the lizard's toes abduct during the stroke phase to create more contact area with the water, increasing the impulse. Then, on recovery up, the toes adduct to prevent contact with the edge of the air pocket [2]. This has been shown to be a passive mechanism, as it occurs even in a lizard foot that has been amputated. The researchers were therefore able to partially imitate the effect by making compliant circular feet with folding joints on either side. The sides would then fold down due to gravity during recovery up. Elastic material was also added to the joints on a second foot design, increasing the effective spring stiffness. These effects combined to create a more intelligent manufactured foot that had reduced drag during recovery [29].

One interesting occurrence that distinguished the robotic runner from the basilisk lizard was the formation of plumes. During recovery up, a plume of water was pulled from the bottom of the air pocket to the bottom of the robot's foot. This resulted in excess splashing, increased drag, faster cavity collapse, and an additional expenditure of energy. It may have been due to contact between the foot and the wall of the air pocket, or the occurrence of a vacuum effect underneath the circular foot. The robot's foot was also made of a more hydrophilic material than the basilisk lizard's foot, which could have resulted in the water clinging to it [29]. Whatever the reason, plume formation is another challenge to overcome in the development of a water running robot. This and other challenges will certainly be worked on in the coming years, with the ultimate goal being a fully autonomous robot that can run on both land and water [29, 31].

Chapter 2

OBJECTIVES

The main objective of this research is to utilize an FDFP to characterize the force interactions of the basilisk lizard running on water. Once the experimental setup is completed, the data collection itself will be relatively straight-forward. The main challenge throughout the past two semesters has been designing and building a setup that is both light and extremely rigid. Due to the small magnitude of the forces being measured and the high sensitivity of the force sensors, low natural frequencies in the setup can create interference with the stride frequency of the lizards, thus preventing the interactions from being accurately measured. These unique design constraints, combined with the novelty of the experiment, created a challenging project in terms of both design and manufacturing.

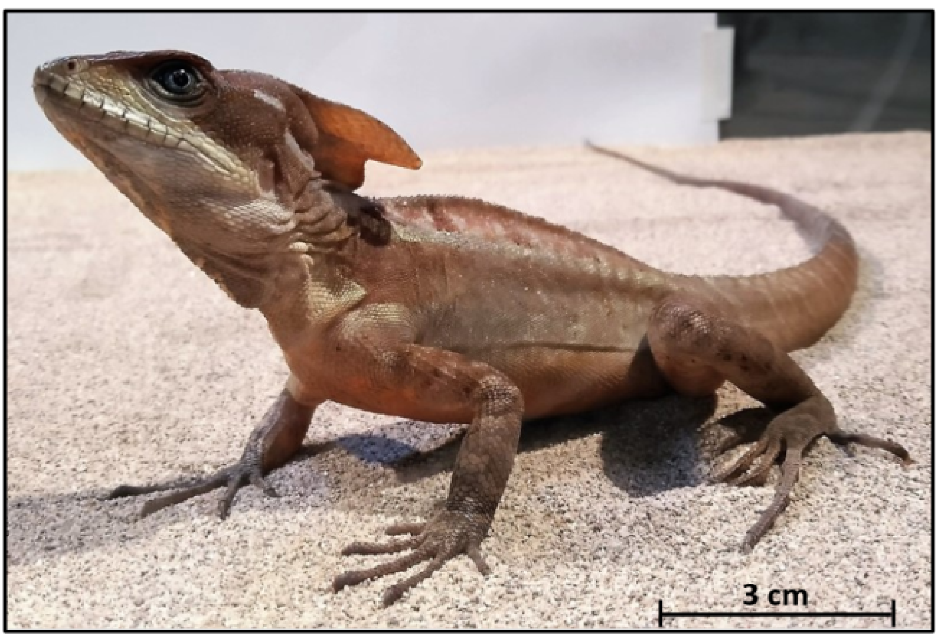

Figure 2.1: A Brown Basilisk Lizard

Chapter 3

EXPERIMENTAL SETUP AND DISCUSSION

3.1 Design of Experimental Setup

Basilisk lizards cannot be trained in the traditional sense. They use running on water as a defense mechanism, and will generally only do it when they perceive a threat. When travelling across water without urgency, they will often choose to swim rather than run. They also need a relatively long distance, around 2 meters, to properly execute a run. With these facts in mind, it was decided that the FDFP would be immersed in the transition track, a 6 meter long, open-topped track that was used in previous research to study the lizards' transitions between different types of terrain. The track has been repurposed such that the middle 2-meter section of track has higher barriers on either end, as well as lower walls on the sides. This enables it to be almost completely filled with water. A box suspended in the water could then go unnoticed by a basilisk lizard running across the track, enabling a seamless recording of its force interactions.

Figure 3.1: A Basilisk Lizard Running on Water in the Original Transition Track

The box needed to be connected to sensors at three statically determinate points. These were created by attaching a shaft structure to the box. This structure was attached using aluminum brackets with multiple holes so that the height could be adjusted as necessary. Cup washers were attached to the underside of the structure using epoxy. These washers rested on top of ball bearings, which were placed in three V blocks. Underneath the V blocks were the sensors, which were mounted to the top of two 8020 aluminum boxes. To prevent unwanted vibrations from external sources such as air conditioning units, Mighty Mounts were selected as the feet of the 8020 supports. Their high level of vibration dampening and shock absorption helps to increase the consistency and clarity of the data.

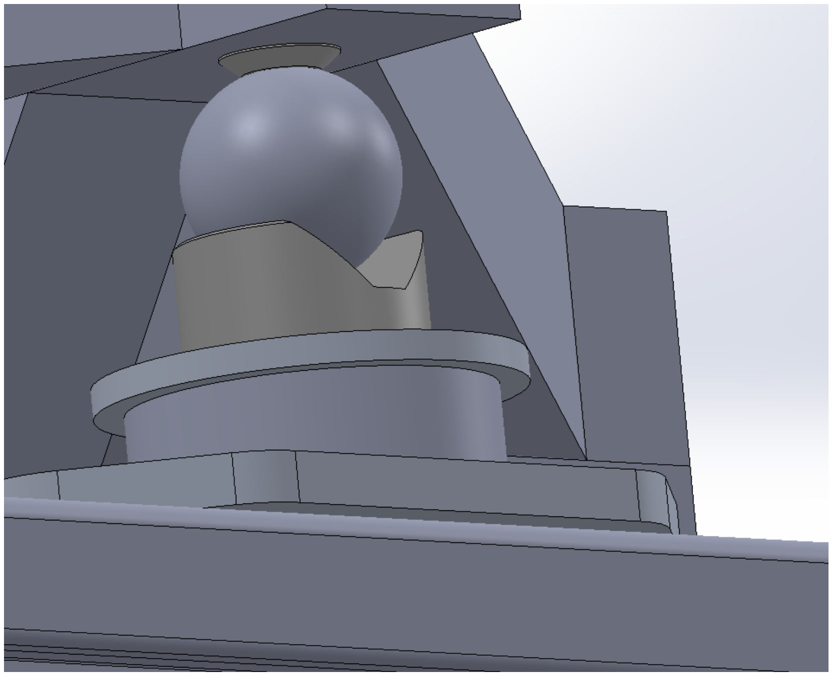

Figure 3.2: Upward View of Sensor Assembly

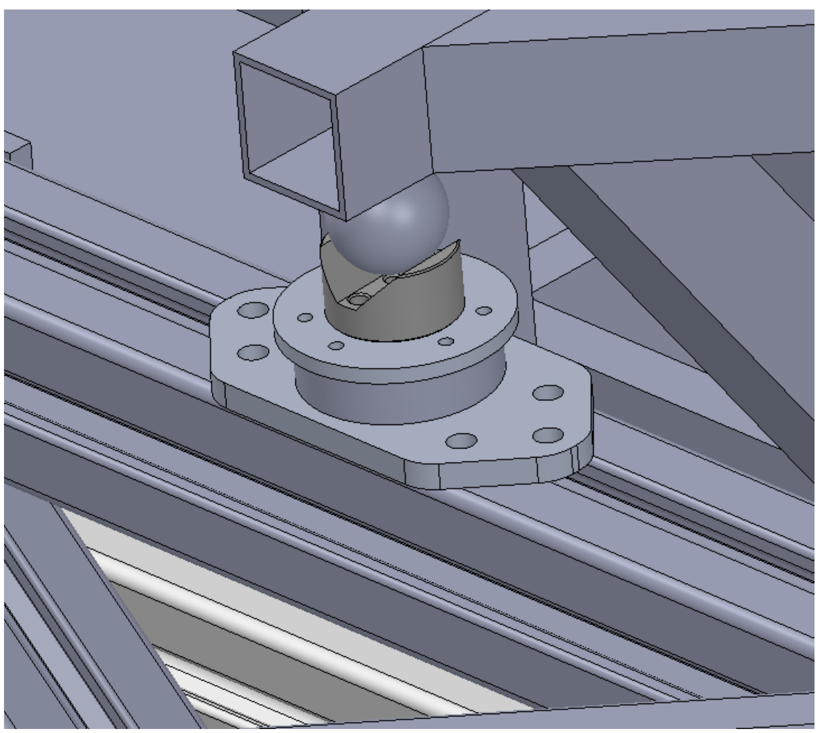

Figure 3.3: Downward View of Sensor Assembly

The box needed to be robust enough for experimental handling; however, in the context of the setup, it is under relatively low stress. This is because the buoyancy of the water supports the box from underneath, balancing out the downward force of the water. The result is a neutrally buoyant box with very little downward force placed on the three sensors. Early designs for the box therefore prioritized its rigidity and low weight over strength. This resulted in the choice of carbon fiber shafts rather than steel. At one point during frequency testing, the water outside of the box was removed before the water inside the box, resulting in a much larger downward force than it was designed to support. The box broke and needed to be repaired. Aside from that misstep, however, the design of the box has not created any problems with the research.

The most prohibitive design restriction of the project concerns the natural frequencies of the setup. Basilisk lizards have a stride frequency of approximately 8 strides per second, or 8 Hz. In order to be confident that the box's natural frequencies would not be misconstrued as stride data, the box was designed to only have frequencies at least 5 times greater than the stride frequency of the lizards. Comsol was used to simulate the box's displacement and natural frequency for different modes, such as those shown in Figures 3.4 and 3.5. This process helped to ensure that the minimum frequency requirement of 40 Hz was being met. The resulting natural frequencies are shown in Table 3.1.

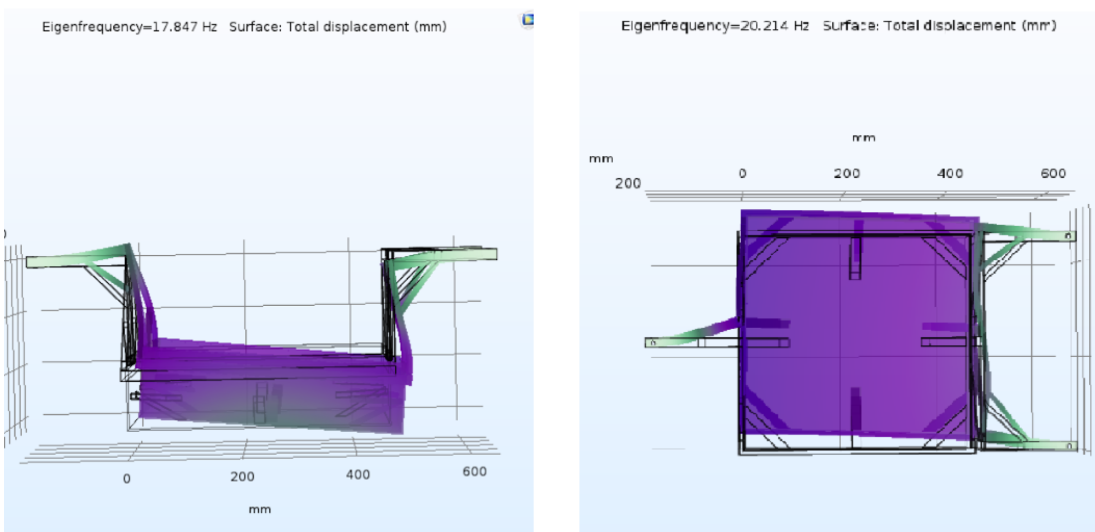

Figure 3.4: Comsol Simulation of Natural Frequency: Mode 1

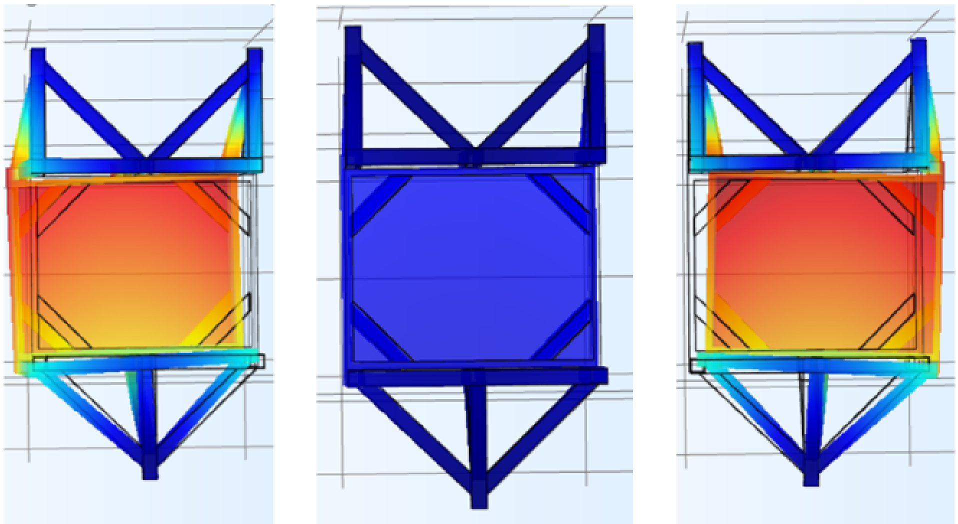

Figure 3.5: Comsol Simulation of Natural Frequency: Mode 2

Mode	Natural Frequency (Hz)
1	55.397
2	113.75
3	140.23
4	251.77
5	343.26
6	443.99

Table 3.1: Natural Frequencies of Setup

Throughout the design process, a Solidworks model of the setup was maintained and updated. This ensured proper dimensioning, as well as facilitating clear communication of ideas during discussion. The final design can be seen in Figure 3.6 below.

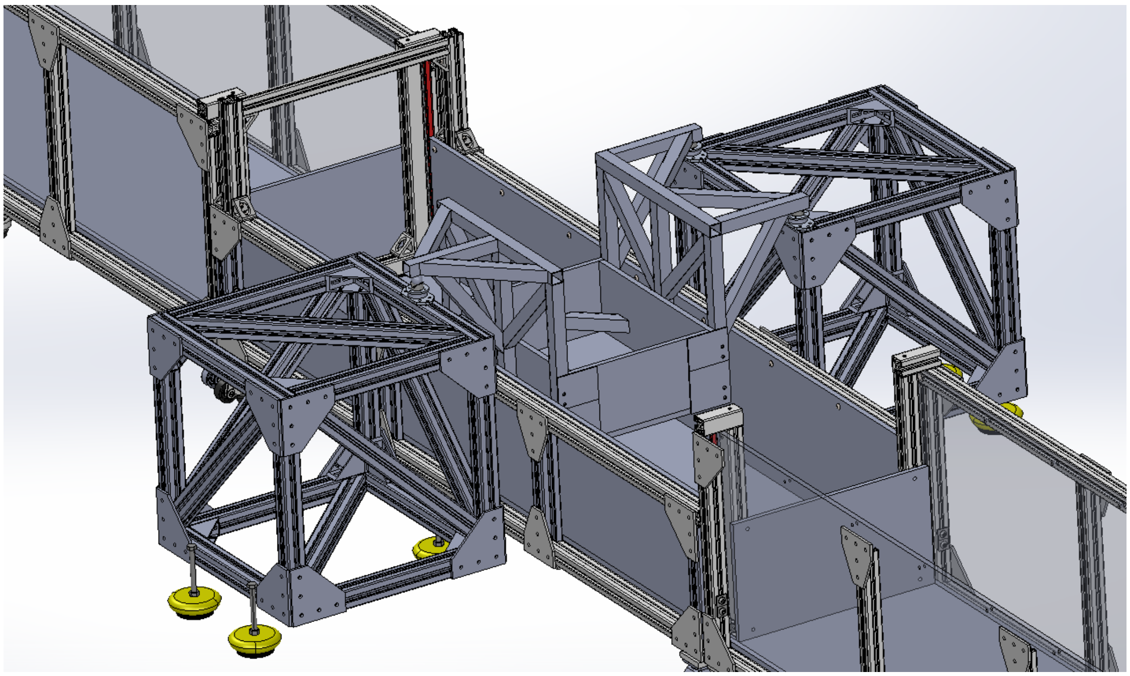

Figure 3.6: Final Solidworks Assembly Model

3.2 Fabrication of Experimental Setup

The shafts connecting the box to the aluminum supports were cut using a diamond saw. They were assembled using Loctite HY 4080 epoxy. To improve the quality of the assembly, a custom part was designed and 3D-printed in the lab that could hold the shafts together overnight while the epoxy hardened (Figure 3.7).

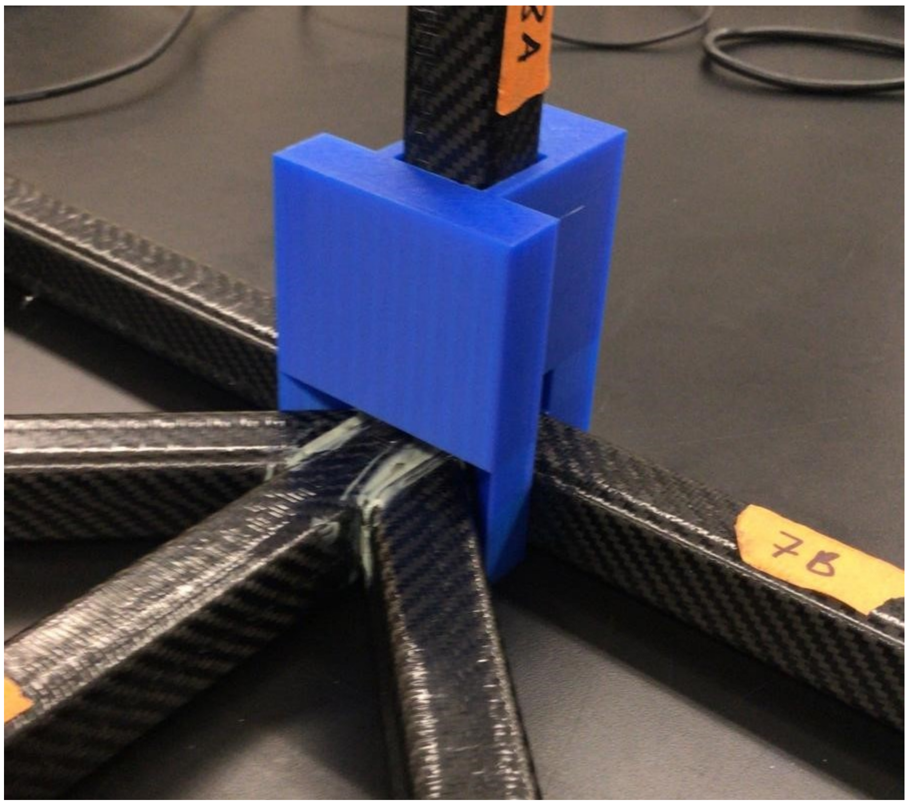

Figure 3.7: 3D Printed Part for Assembling Carbon Fiber Frame

For the box itself, carbon fiber reinforced polymer (CFRP) was selected as a sufficiently rigid material. A sheet of CFRP with a foam core was purchased to make the box lighter. It was cut into the four walls and floor of the box by Southwest Water Corporation. The walls were then assembled using epoxy (Figure 3.8). They were fortified using short 45-degree shafts that connected each wall to both adjacent walls. Lastly, the joints were treated with silicone and tested to ensure the box was completely watertight.

Figure 3.8: CFRP Box Freshly Assembled with Epoxy

Four aluminum brackets were cut and drilled. The four carbon fiber shafts on the corners of the box were drilled using a diamond-tipped drill bit. The brackets were fastened to the shafts using nuts and bolts. They were then attached to the sides of the box using epoxy (Figure 3.9).

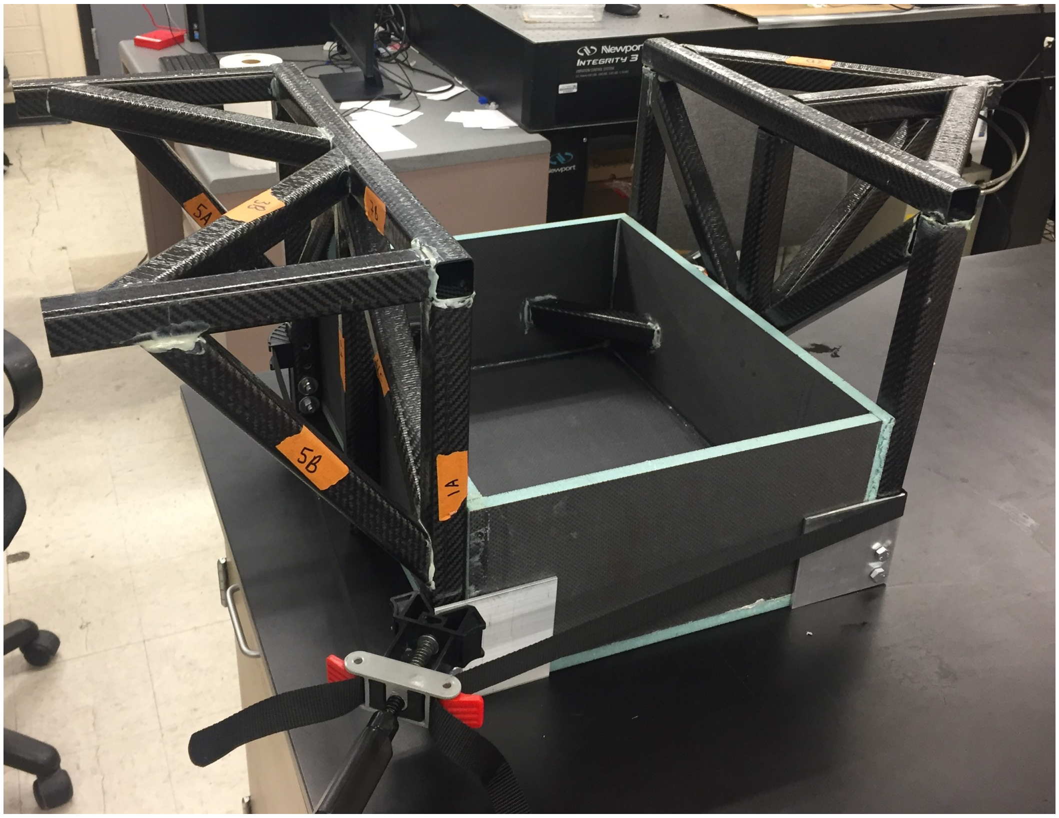

Figure 3.9: Carbon Fiber Shafts Attached to CFRP Box with Epoxy

An additional fabrication challenge came from the transition track. The original experiments did not require a secondary setup suspended inside of it. This design constraint required modification of the track's walls, which were taller than the 8020 supports. The middle section of the track's walls were therefore disassembled, and new 8020 and acrylic were installed with a length of 10" instead of 18". The other two sections of the track were not modified, as only the middle section needs to accommodate the height of the box setup.

The completed experimental setup can be seen in Figure 3.10 below. With the center section of the track shortened, the 8020 supports are tall enough to suspend the box inside the track without creating any physical contact.

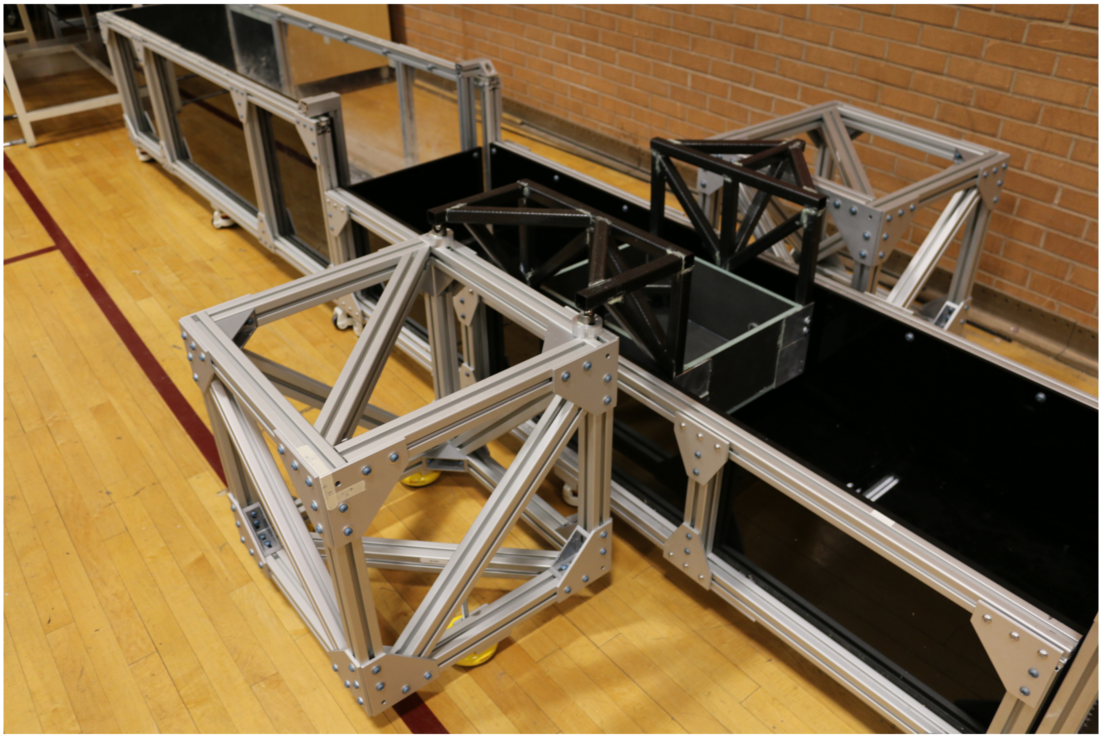

Figure 3.10: Complete Setup of Track with Box Suspended from 8020 Supports

3.3 Frequency Testing

Once the box setup was completely assembled, its natural frequencies needed to be tested. The test that we conducted was based on the test used for the AFP research. A small hammer was constructed from a carbon fiber rod and a nylon nut. The accelerometer was mounted to six different points on the setup, with beeswax applied beforehand to improve the strength of the connection. After beginning data collection, the setup was then tapped with the hammer near the accelerometer in the x, y, and z directions. The process is summarized in Figure 3.11 below.

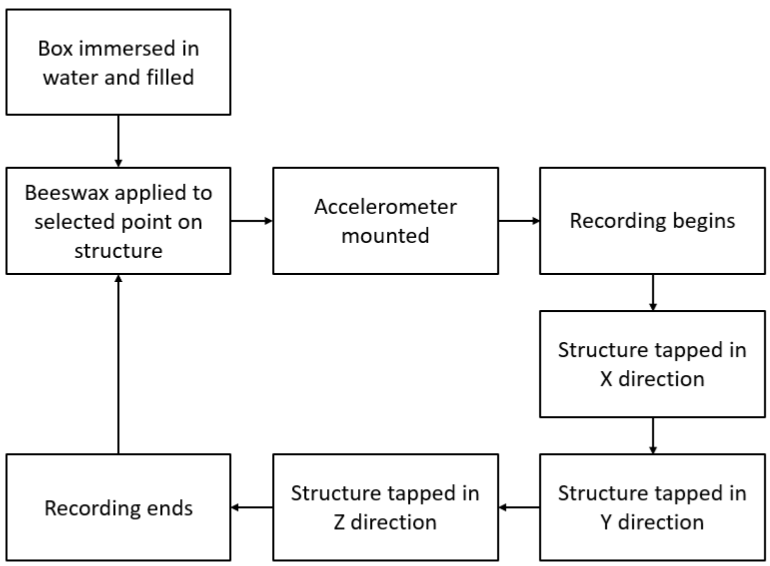

Figure 3.11: Procedure Flow Chart

The six locations that were tested for natural frequencies are labelled in Figure 3.12. The intent was not necessarily to collect data for every point on the setup, but to select points that represented the majority of critical locations. It is assumed, for example, that the data collected for one corner of the CFRP box is fairly representative of the other three box corners as well.

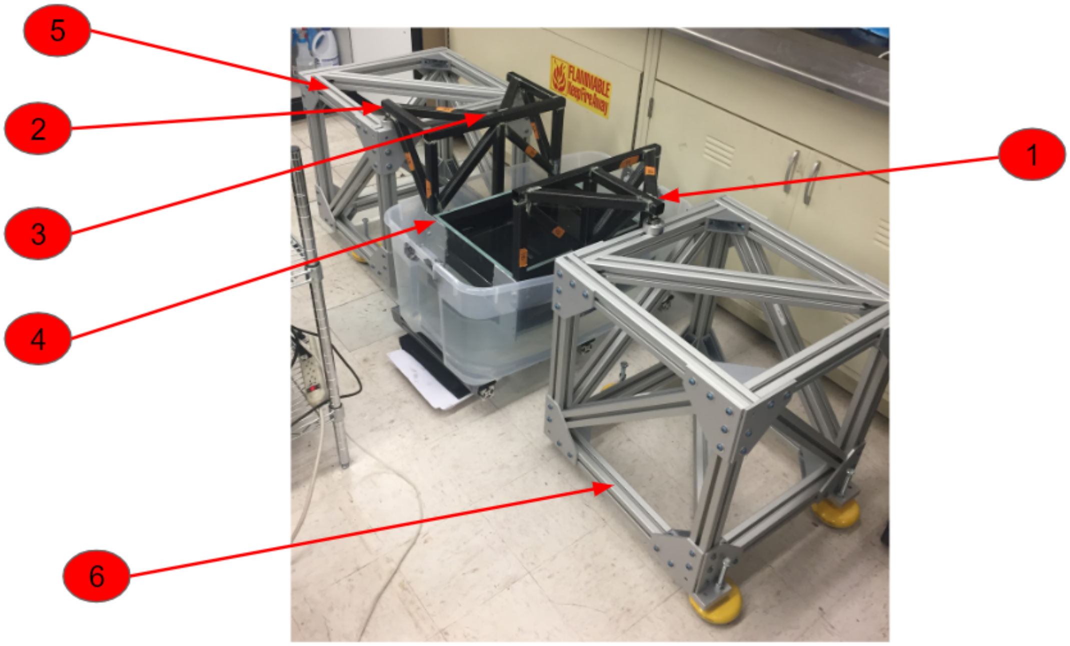

Figure 3.12: Frequency Test Locations

Chapter 4

PRELIMINARY RESULTS

The primary results of this research have not yet been collected. They will ultimately be in the form of plots of the horizontal and vertical forces on the lizard with respect to time. This data will also be synchronized with OptiTrack recordings of the lizards running, providing a greater understanding of the forces and torques acting on the lizard at different points in its stride.

At this time, the results consist of data intended to validate that the setup was assembled correctly and that the initial simulations were accurate. The acceleration data obtained from the accelerometer during the frequency test was integrated twice to obtain position data. For each trial's data, the periods immediately after the structure had been struck by the carbon fiber hammer were isolated. The number of data points was linearly interpolated to the next highest power of 2 to ensure that no data points were unused. A fast Fourier transform (FFT) was then performed using MATLAB, and the resulting frequencies from taps in the x, y, and z directions were plotted on a single graph for each accelerometer location. The results are displayed in Figures 4.1-4.6.

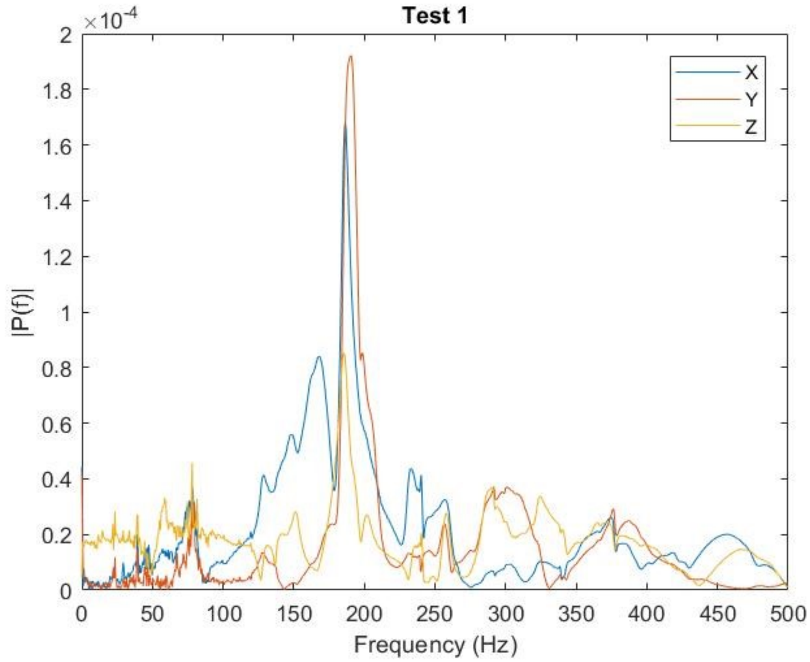

Figure 4.1: Test 1: Accelerometer Placed above Paired Sensor

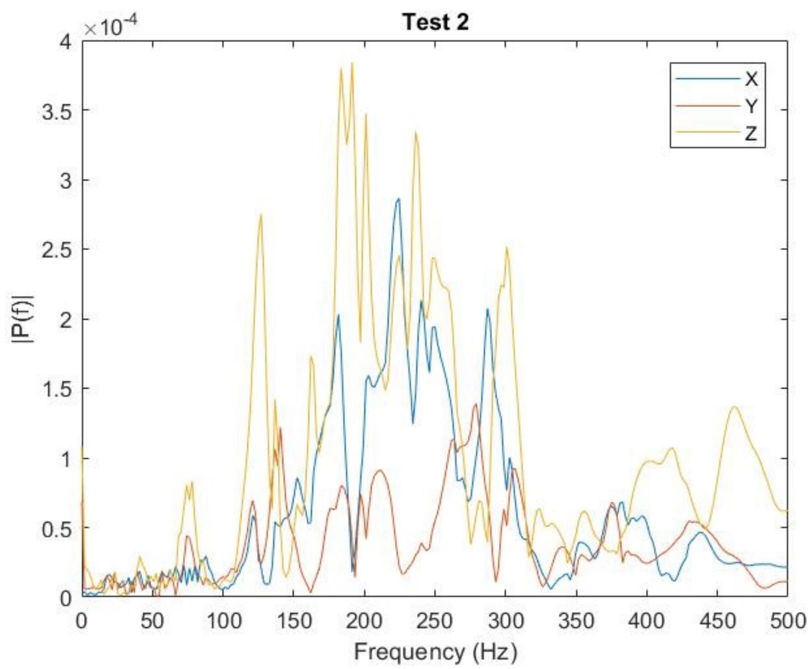

Figure 4.2: Test 2: Accelerometer Placed Between Paired Sensors

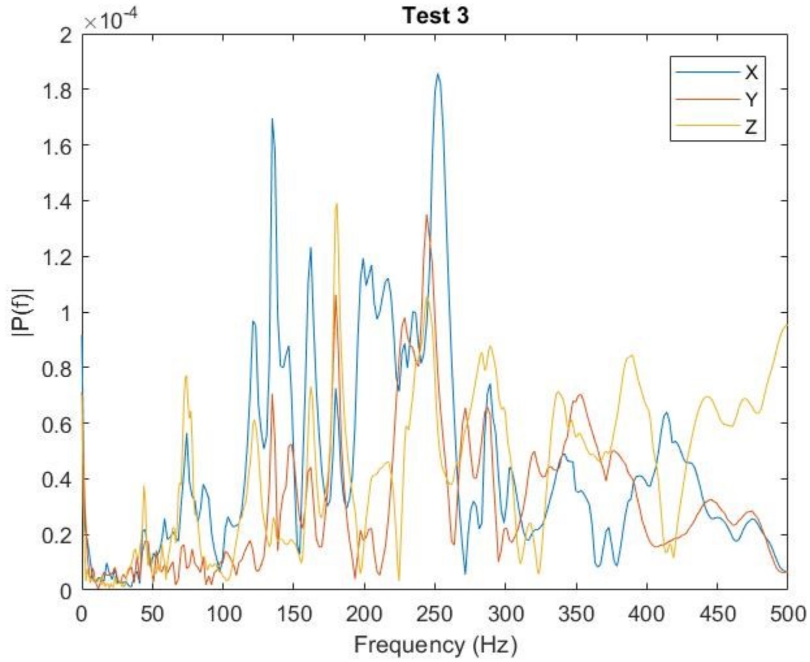

Figure 4.3: Test 3: Accelerometer Placed on Corner of Box

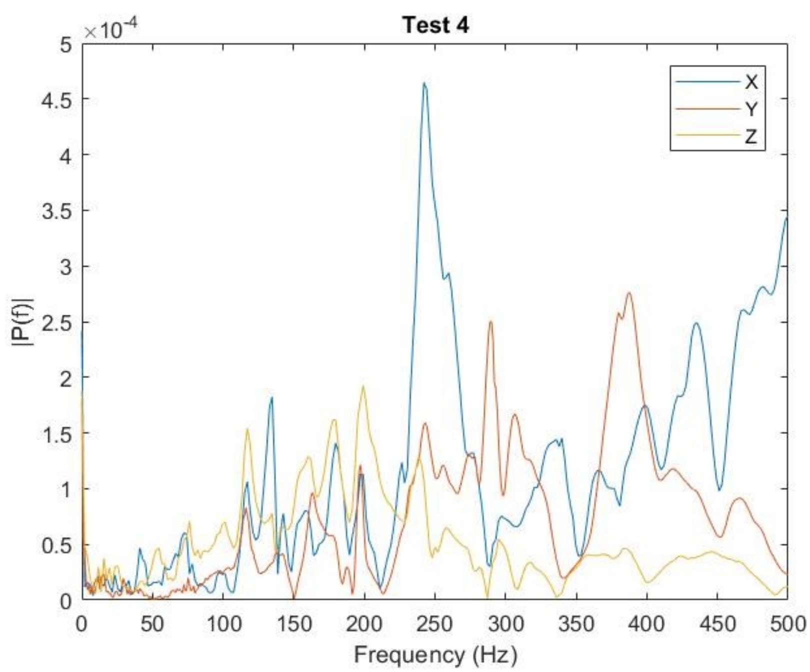

Figure 4.4: Test 4: Accelerometer Placed above Unpaired Sensor

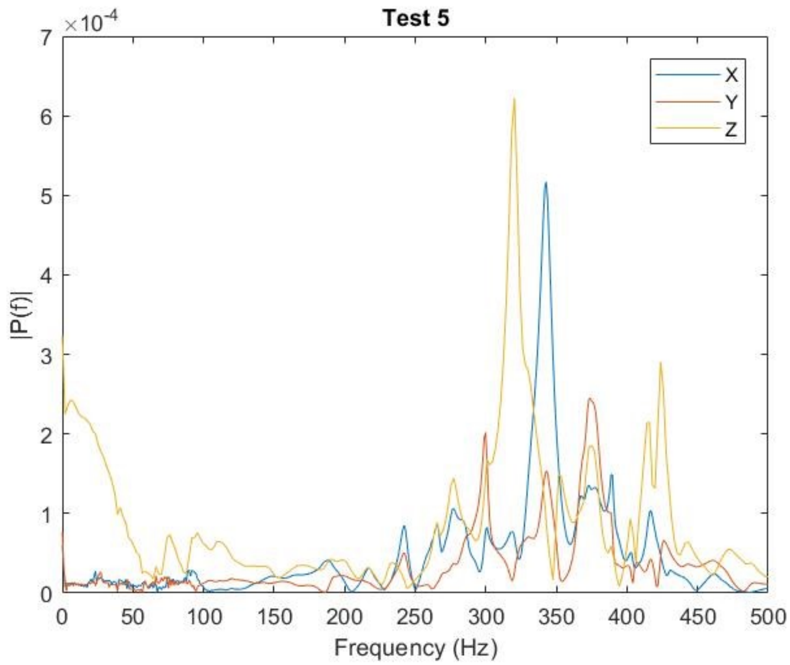

Figure 4.5: Test 5: Accelerometer Placed on Top 8020 Support

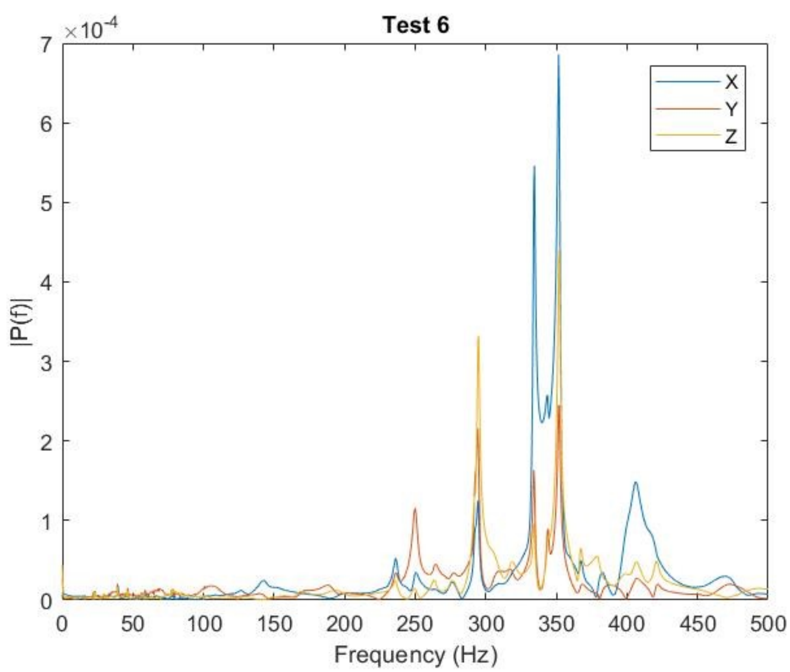

Figure 4.6: Test 6: Accelerometer Placed on Bottom 8020 Support

From the data, we are able to confirm that the majority of locations on the setup did not return magnitude peaks at frequencies below 40 Hz. Two tests that are in need of greater scrutiny are the z-direction strikes on Tests 1 and 5. Any such peak could indicate a characteristic of the setup that could potentially interfere with the lizard data. Moving forward, we plan to conduct additional frequency tests and address any problems that become apparent. This could, for example, entail adding additional carbon fiber shafts in order to make the structure more rigid. These steps will ensure that system noise will be kept to a minimum in the final results.

Chapter 5

CONCLUSION AND FUTURE RESEARCH

5.1 Conclusion

This thesis has summarized the effort so far in directly recording the force interactions of a basilisk lizard running on water. The data ultimately collected by this project will be the first of its kind. This is due to both the novelty and the difficulty of developing a fluid dynamic force platform that can accurately record the necessary kinematics. By developing a setup that is capable of recording such forces accurately, this project has made significant progress toward a complete characterization.

5.2 Future Research

Much of the work presented in this thesis has been preliminary. The next step will be to construct a force validation fixture that can confirm the readings from the three sensors using an external force sensor. The goal is to roughly approximate the event of a lizard's foot slapping the water. Therefore, the design includes a linear actuator appended with a simple 3D-printed shape to represent the lizard's foot. The external sensor is attached to the bottom of the foot. This assembly will be mounted on the transition track rather than the 8020 supports so that it does not interfere with the three sensors that the box is mounted on. It will be suspended above the box, and the actuator will be rapidly extended into the water. The two separate force measurement systems can then be compared to ensure consistent readings. The model of the force validation setup can be seen individually in Figure 5.1 below, as well as in Figure 5.2 mounted on the larger setup.

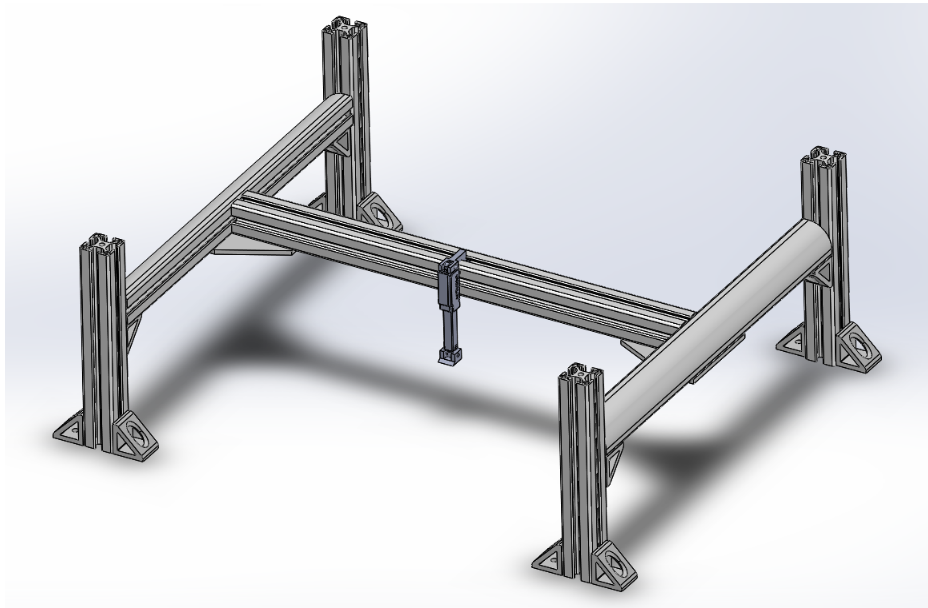

Figure 5.1: Force Validation Fixture

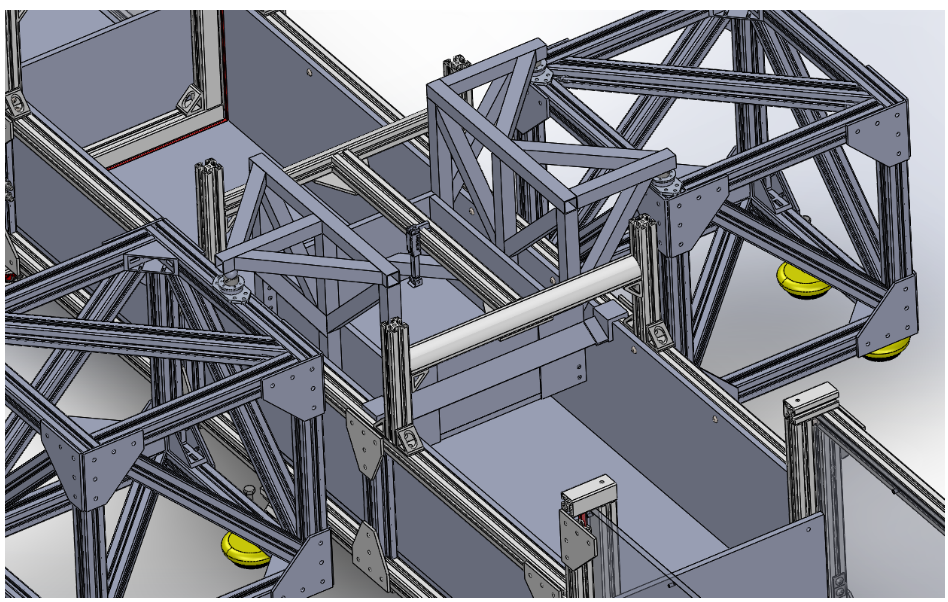

Figure 5.2: Force Validation Fixture Mounted to Setup

In the near future, this project will begin animal testing. It is difficult to predict the behaviors that the lizards will exhibit once exposed to the setup, and there will likely be adjustments needed to foster the correct behavior. Once the setup has been confirmed to be compatible with the lizards, the Nano 43 sensors will be acquired from our collaborators. At this point, the animal trials will begin. The lizards will be fitted with waterproof markers at critical locations such as their head, pelvis, and center of mass. This will enable the data obtained from the three force sensors to be cross-referenced with that of OptiTrack cameras. A high FPS camera placed inside the CFRP box will be especially useful for understanding the timing of each phase of the stride with respect to the forces occurring. This will result in a kinematic characterization of this unique method of locomotion that will hopefully be useful for the development of water-running robots.

REFERENCES

[1] Michael Mangan, Mark Cutkosky, Anna Mura, Paul F.M.J. Verschure, Tony Prescott, and Nathan Lepora, editors. *Biomimetic and Biohybrid Systems*, volume 10384 of *Lecture Notes in Computer Science*. Springer International Publishing, Cham, 2017.

[2] S. T. Hsieh. Three-dimensional hindlimb kinematics of water running in the plumed basilisk lizard (Basiliscus plumifrons). *Journal of Experimental Biology*, 206(23):4363–4377, December 2003.

[3] Steve H. Suhr, Yun Seong Song, Sang Jun Lee, and Metin Sitti. Biologically Inspired Miniature Water Strider Robot. In *Robotics: Science and Systems I*. Robotics: Science and Systems Foundation, June 2005.

[4] John W.M. Bush and David L. Hu. WALKING ON WATER: Biolocomotion at the Interface. *Annual Review of Fluid Mechanics*, 38(1):339–369, January 2006.

[5] Hyun Soo Park and Metin Sitti. Compliant footpad design analysis for a bio-inspired quadruped amphibious robot. In *2009 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 645–651, St. Louis, MO, USA, October 2009. IEEE.

[6] Hyun Soo Park, S. Floyd, and M. Sitti. Dynamic modeling and analysis of pitch motion of a basilisk lizard inspired quadruped robot running on water. In *2009 IEEE International Conference on Robotics and Automation*, pages 2655–2660, Kobe, May 2009. IEEE.

[7] Ali Mohebbian and David E. Rival. Assessment of the derivative-moment transformation method for unsteady-load estimation. *Experiments in Fluids*, 53(2):319–330, August 2012.

[8] Ben J Hightower, Rivers Ingersoll, Diana D Chin, Carl Lawhon, Andreas F Haselsteiner, and David Lentink. Design and analysis of aerodynamic force platforms for free flight studies. *Bioinspiration & Biomimetics*, 12(6):064001, October 2017.

[9] Diana D. Chin and David Lentink. How birds direct impulse to minimize the energetic cost of foraging flight. *Science Advances*, 3(5):e1603041, May 2017.

[10] D. Lentink, A. F. Haselsteiner, and R. Ingersoll. In vivo recording of aerodynamic force with an aerodynamic force platform: from drones to birds. *Journal of The Royal Society Interface*, 12(104):20141283–20141283, January 2015.

[11] David Lentink. Accurate fluid force measurement based on control surface integration. *Experiments in Fluids*, 59(1), January 2018.

[12] S. Tonia Hsieh. Three-axis optical force plate for studies in small animal locomotor mechanics. *Review of Scientific Instruments*, 77(5):054303, May 2006.

[13] Richard C. Snyder. Bipedal Locomotion of the Lizard Basiliscus basiliscus. *Copeia*, 1949(2):129, June 1949.

[14] Hosain Bagheri, Vishwarath Taduru, Sachin Panchal, Shawn White, and Hamidreza Marvi. Animal and Robotic Locomotion on Wet Granular Media. In Michael Mangan, Mark Cutkosky, Anna Mura, Paul F.M.J. Verschure, Tony Prescott, and Nathan Lepora, editors, *Biomimetic and Biohybrid Systems*, volume 10384, pages 13–24. Springer International Publishing, Cham, 2017.

[15] Duncan J Irschick and Bruce C Jayne. EFFECTS OF INCLINE ON SPEED, ACCELERATION, BODY POSTURE AND HINDLIMB KINEMATICS IN TWO SPECIES OF LIZARD CALLISAURUS DRACONOIDES AND UMA SCOPARIA. page 15, 1998.

[16] Joshua Laerm. Aquatic Bipedalism in the Basilisk Lizard: The Analysis of an Adaptive Strategy. *American Midland Naturalist*, 89(2):314, April 1973.

[17] Joshua Laerm. A Functional Analysis of Morphological Variation and Differential Niche Utilization in Basilisk Lizards. *Ecology*, 55(2):404–411, March 1974.

[18] A. Stanley Rand and Hymen Marx. Running Speed of the Lizard Basiliscus basiliscus on Water. *Copeia*, 1967(1):230, March 1967.

[19] Yun Seong Song and Metin Sitti. STRIDE: A Highly Maneuverable and Non-Tethered Water Strider Robot. In *Proceedings 2007 IEEE International Conference on Robotics and Automation*, pages 980–984, Rome, Italy, April 2007. IEEE.

[20] David L. Hu, Brian Chan, and John W. M. Bush. The hydrodynamics of water strider locomotion. *Nature*, 424(6949):663–666, August 2003.

[21] Sun Gi Park, Min Chul Lee, Hyeong Jun Tak, and Jong Soo Ko. Analysis of force and impulse of a hydrophobic rod rotating into water. *Micro and Nano Systems Letters*, 7(1):1, December 2019.

[22] J.W. Glasheen and T.A. McMahon. A hydrodynamic model of locomotion in the basilisk lizard. *Letters to Nature*, 380, 1996.

[23] D. Sharma, A. Erriguible, and S. Amiroudine. Numerical modeling of the impact pressure in a compressible liquid medium: application to the slap phase of the locomotion of a basilisk lizard. *Theoretical and Computational Fluid Dynamics*, 31(3):281–293, June 2017.

[24] S. T. Hsieh and G. V. Lauder. Running on water: Three-dimensional force generation by basilisk lizards. *Proceedings of the National Academy of Sciences*, 101(48):16784–16788, November 2004.

[25] J W Glasheen and T A Mcmahon. SIZE-DEPENDENCE OF WATER-RUNNING ABILITY IN BASILISK LIZARDS. page 8.

[26] Steven Floyd, Terence Keegan, John Palmisano, and Metin Sitti. A novel water running robot inspired by basilisk lizards. *IEEE Intelligent Robotics Systems*, 2006.

[27] Yun Seong Song and M. Sitti. Surface-Tension-Driven Biologically Inspired Water Strider Robots: Theory and Experiments. *IEEE Transactions on Robotics*, 23(3):578–589, June 2007.

[28] Dong Gyu Lee, HyunGyu Kim, Kyungmin Jeong, and Teawon Seo. Development of a robotic platform for amphibious locomotion on ground and water surfaces. In *2014 11th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI)*, pages 417–418, Kuala Lumpur, Malaysia, November 2014. IEEE.

[29] Steven Floyd, Serhat Adilak, Steven Ramirez, Raphael Rogman, and Metin Sitti. Performance of different foot designs for a water running robot. In *2008 IEEE International Conference on Robotics and Automation*, pages 244–250, Pasadena, CA, USA, May 2008. IEEE.

[30] Hyun Soo Park, Steven Floyd, and Metin Sitti. Roll and Pitch Motion Analysis of a Biologically Inspired Quadruped Water Runner Robot. *The International Journal of Robotics Research*, 29(10):1281–1297, September 2010.

[31] Steven Floyd and Metin Sitti. Design and Development of the Lifting and Propulsion Mechanism for a Biologically Inspired Water Runner Robot. *IEEE Transactions on Robotics*, 24(3):698–709, June 2008.