Title
A three-axis force platform design for cockroach incline climbing analysis

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Publication Date
2019

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA SAN DIEGO

A three-axis force platform design for cockroach incline climbing analysis

A thesis submitted in partial satisfaction of the
requirements for the degree
Master of Science

in

Engineering Sciences (Mechanical Engineering)

by

Qin Qin

Committee in charge:

Professor Nicholas Gravish, Chair
Professor Mauricio de Oliveira
Professor Tania Morimoto

2019

The thesis of Qin Qin is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

Chair

University of California San Diego

2019

EPIGRAPH

Chance is the name we give to what we choose to ignore.

Voltaire

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ACKNOWLEDGEMENTS

I would like to give my special thanks to my thesis advisor Prof. Nicholas Gravish. He gave me a lot of constructive advice and guidance during this project. I am very grateful to work in Gravish Lab.

I would like to thank Prof. Mauricio de Oliveira and Prof. Tania Morimoto for serving on my dissertation committee. I really appriciate their time and efforts.

I would like to thank all the members in Gravish Lab. They supported me a lot and were always willing to help.

I would also like to thank my family and my friends for their support and encouragement. They are always there for me.

Last but not least, I would like to thank Geisel Library for providing such a nice place to study and read.

VITA

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ABSTRACT OF THE THESIS

A three-axis force platform design for cockroach incline climbing analysis

by

Qin Qin

Master of Science in Engineering Sciences (Mechanical Engineering)

University of California San Diego, 2019

Professor Nicholas Gravish, Chair

Insects like cockroach run and climb with great speed and adaptability compared to their sizes. Researchers have been studying on the kinematic of insect for a long time and many climbing robots have been designed using cockroach as prototype, but no one has comparable performance with cockroach. The study of single leg ground reaction force exerted by incline-climbing cockroach gives valuable intuition to design the locomotion of climbing robots.

To better study the kinematic and locomotion of cockroach incline climbing, a three-axis force platform has been designed and fabricated. The force platform consists of a force plate made with a handmade mechanical structure and a carbon fiber surface. The force plate has four force measurement channels including two vertical channels, medio-lateral channel and fore-aft channel with typical sensitivities of 3.46 V/N, 2.11 V/N, 4.42 V/N and 5.76 V/N. The natural frequency of the force platform is around 200 Hz. The compatible apparatus setup including running trackway, strain-gauge tree, tilting device has also been introduced. This paper presents detailed design and fabrication with calibration procedure and performance test, and the result of the test experiment shows that this force platform meets the requirements of studying large insects biomechanics.

Chapter 1

Introduction

1.1 Motivation

Insects exert great power during running and climbing. When an insect runs or climbs, it generates mechanical force to move vertically and horizontally. For researchers in legged robot field, insects like cockroaches represent the paradigm of efficient and effective movement. Because they exemplary not only for their speed and agility, but also for their ability to traverse many difficult terrains. For the American cockroach *Periplaneta americana*, a small, rapidly running species, can run at speeds in a range of 1.0 to 1.5 m/s or 50 body-lengths/s [Full and Koehl, 1993]. For a larger and slower species, South American tropical cockroach *Blaberus discoidalis*, has been confirmed to navigate around obstacles three times the height of its mass center without noticeable reduction in speed [Full et al., 1998]. Since there is no robots can compare such performance, cockroaches have been addressed as the prototype of many bio-inspired hexapod running robots [Jong-ung Choi et al., 2005].

For the analysis of animals' leg ground reaction force, commercially available force platforms are generally designed for the analysis of human beings and other comparatively large animals, but these force platforms are not useful for the study of rather small animals. As for the commercially available force platforms for small animals like insects do have good performance but the cost is expensive. Therefore, a customized force platform that has relatively close performance and costs less is desirable for the study of cockroaches.

1.2 Current work of art

To study the locomotion and kinematics of cockroaches and other small animals like geckos, researchers have developed a variety of customized apparatus to measure the ground reaction force of their limbs. In 1978, Harris introduced a photoelastic substrate technique for dynamic force measurements [Harris, 1978]. By having the small organisms move on a photoelastic substrate made by gelatin, the applied stress can be transduced into an optical birefringence signal which can be interpreted to provide static force measurements. The apparatus was three axis gel and the animal it studied was crickets which has an average weight of 0.435 g. This method has also been applied to the study of cockroaches, which the typical force measurement for a single cockroach leg is 10 mN [Full et al., 1995].

Another method that was presented in early 2000s is the use of microelectromechanical systems (MEMS) for the study of insects biomechanics [Bartsch et al., 2000, Bartsch et al., 2001, Bartsch et al., 2003]. The multi-axis sensor with micro Newton resolution comprised a rigid central plate that was supported by four beams with piezoresistive transducers on each corner [Bartsch et al., 2007], which determined the measurement of both normal and in-plane bending force components.

While in 1989, Full and Tu designed a two axis force platform based on small handmade mechanical structures with strain gauges glued on the spring blade elements [Full and Tu, 1990], which was used to study cockroaches. This one is the most widely used method to study the several components of the ground reaction force. This method has

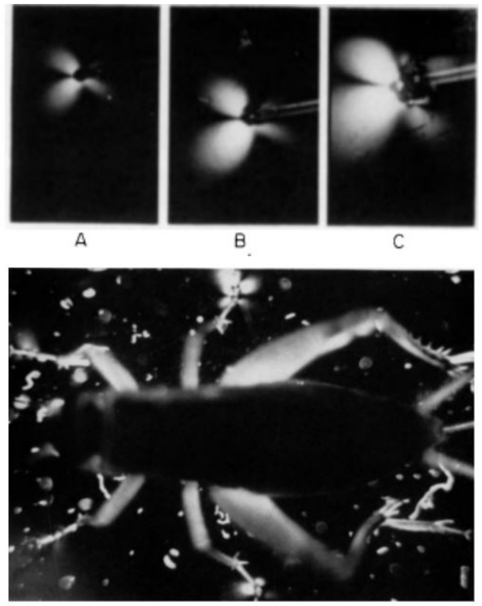


Figure 1.1: Photoelastic substrate technique [Harris and Ghiradella, 1980].

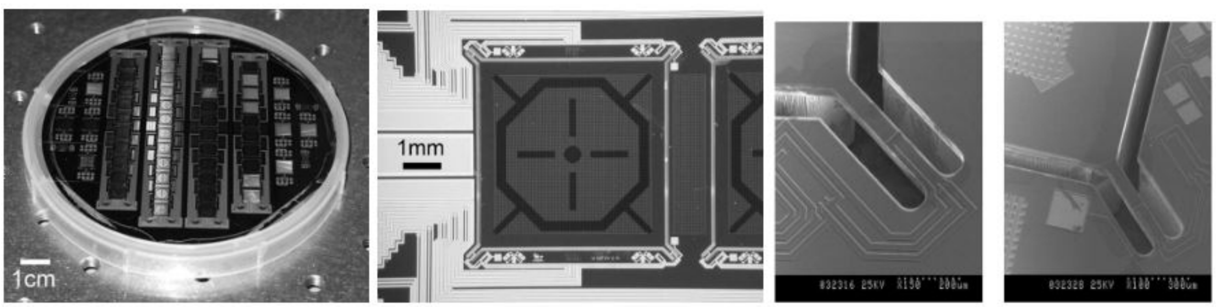
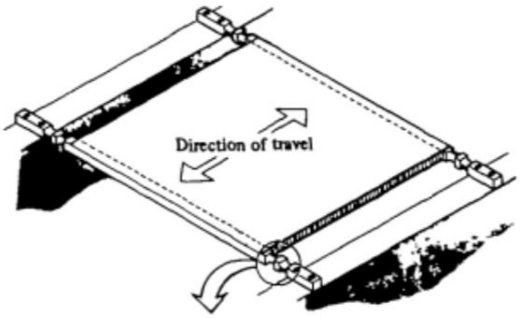


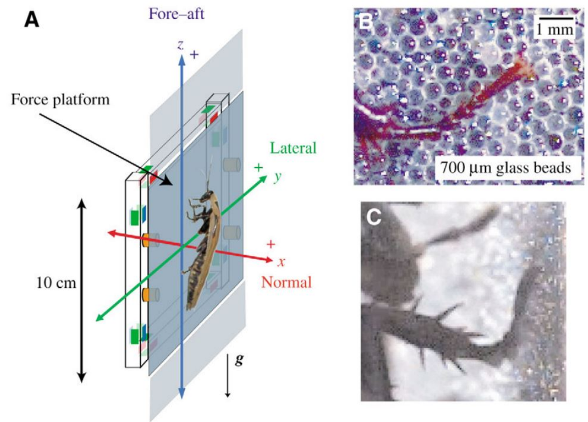
Figure 1.2: Sensor array on waffles and optical micrograph showing individual sensor element [Bartsch et al., 2007].

been modified and upgraded to a three axis force plate later [Goldman et al., 2006].

In this work, a method for designing a three dimensional force sensor plate is discussed. We designed a force platform that can detect the ground reaction force exerted by an insect when its limb is landing on the surface of the platform. This platform can also be used to record the ground reaction force of other large insects and small animals. Along with the vertical force analysis, the force platform can also detect fore-aft force and lateral force. Since some insects like cockroaches are different from many mammals, which walk and run in an upright fashion, they run with a sprawled posture gait with their limbs



(a)



(b)

Figure 1.3: Spring blade elements force plate [Full and Tu, 1990] and modified three dimensional force plate [Goldman et al., 2006].

extending laterally to their center of mass [Biewener, 1992]. The frame of the force plate is made with hollow brass tubes, which have milling slots on the several surfaces, and the brass tubes are soldered together to form a pound-sign like shape. The surface sheet is made with laminated carbon fiber, which is light weighted. The force plate frame and the surface carbon fiber sheet are connected by four small cylindrical acrylic pieces so the input force is recorded from four specific points. Strain-gauges are used to transduce force based on deflections of slots that work as spring blade elements. The force platform is inserted into the running substrate as a whole part. The good thing about this method is that it is not expensive and all the materials are available in the laboratory. The framework of the apparatus is constructed with 80/20 T-Slotted framing and fittings, and the tilting device is made with the 80/20-compatible pivots.

Chapter 2 discusses about the requirement of the force plate design and gives the details of the force plate geometry and its fabrication. It also gives insights on the equipment used during fabrication. The whole fabrication process is mostly done by using the other mill and the glow forge laser cut.

Chapter 3 gives a brief introduction of the strain-gauge and other electronic considerations. It also gives the reason why some electronic components are chosen. There are also details on how to build the circuit including Wheatstone Bridge and amplifier. Detailed strain-gauge mounting process is also mentioned.

Chapter 4 discusses about the design of the whole apparatus. The detailed geometry of the running substrate and the arrangement of the strain-gauge tree are given in this chapter. It also talks about the force plate calibration. Very detailed outlook on the calibration process is presented. We also test the whole force platform with mini-hexbug. The hexbug runs at inclined substrate of different angle from 0° to 15° and the outputs of the strain-gauge are measured along with the NI DAQ. The outputs match well with the calibration results.

Chapter 5 concludes the future work that needs to be done to refine the force platform so it can be used to study even smaller robots. It also summarizes this research project with objects achieved and future goals.

Chapter 2

Force plate design and fabrication

2.1 Requirements

Force platforms are instruments that record the ground reaction forces exerted by a cockroach when its limb landing on the surface of the platform during one stride as well as pushing or pulling forces. To meet the requirement for this force plate, the following criteria are very important:

- ☐ **High frequency response**

  The high speed camera will be used in the cockroach incline climbing experiment to decide when the cockroach firstly touch and leave the force plate so the ground reaction force of the single leg force can be recorded, so the force platform should have high frequency response to work with high speed camera.

- ☐ **Uniform response over the force plate's surface**

  Within an appropriate range of force, the force plate should be as sensitive as possible. In addition to the sensitivity in the recording force range, the force plate should also be insensitive to the position where the force is applied.

☐ **Independent force measurement in three axis**

In this project, cockroaches' limb ground reaction force is chosen to be studied. It has been shown that limb forces of cockroaches change from pushing force to pulling force as the increase of the inclined surface angle within the range of 0° and 90°. Insects' running and climbing are not like mammals. During the study of other animals, which move their legs in a parasagittal plane, the medio-lateral force that act on their leg is generally small compared to the vertical force and fore-aft force. The medio-lateral force is ignored in usual studies because it will significantly simplify the kinematic calculations. On the contrary, insects rely much on the medio-lateral force, so a three dimensional force measurement is required. Here the ground reaction force is decomposed into three dimensions, which are vertical force, medio-lateral force and fore-aft force. Thus the influence of force change from each dimension can be analyzed separately.

☐ **Low cross talk between three force channels**

Whether there are two or three dimensions to be measured is decided above. It is also very important that the cross influence between either two of three channels should be low, typically less than 3 %. Apart from the low cross influence, the force plate should be designed to have a sufficiently high frequency response. That is to say the force plate's natural frequency, also known as its unloaded natural frequency of response, should be high enough so that the highest frequency components of the ground reaction force can be safely recorded. Generally speaking, the natural frequency of the force platform should be of an order greater than the primary signal frequency.

☐ **Linear response over a sufficient range of force measurement**

The output signal of the force plate should be linear in response to the force applied in all three force channels over the whole range of the forces to be studied.The force platform should be designed to safely measure at least 10 times of the maximally anticipated load [Biewener, 1992]. The animal to be studied in the following test is South American tropical cockroach *Blaberus discoidalis*, which has an average weight of 2.5 g to 3.5 g. Knowing the weight of the animal to be studied, the peak load of the force platform will be designed as 0.2 N.

- ☐ **Sufficient sensitivity for force measurement**

  The force platform should be sufficiently sensitive to record a force of 0.5 mN, and also have a sufficient range to embrace all the primary signal since the limb forces of cockroaches have a wide range. However, there is a trade-off between sensitivity and the range of the force platform. Ideally the force platform should be less sensitive to the position where insects land their feet, while at the same time give a linear output in response to the applied force.

- ☐ **Well designed dimension of the force plate's surface according to the insect to be studied**

  The overall surface of the force plate should be designed to fit the size of the animal to be tested. Technically speaking, the size of the animal includes its foot size, stride length, and length between the lateral limbs on two sides of the center mass. The size of the surface also depends on how the force analysis will be carried out. In this study, one or more complete strides is desirable for the force measurement, so the length of the surface should be long enough to span the animal's entire stride length. The width of the surface should be accordance to the width of the whole running trackway, which should fit the space that the animal needs to move.

- ☐ **Good durability**

Finally, the durability of the force platform should be taken into account. The following tests and experiments are going to be done multiple times, and different animals and insects will be tested on the force platform.

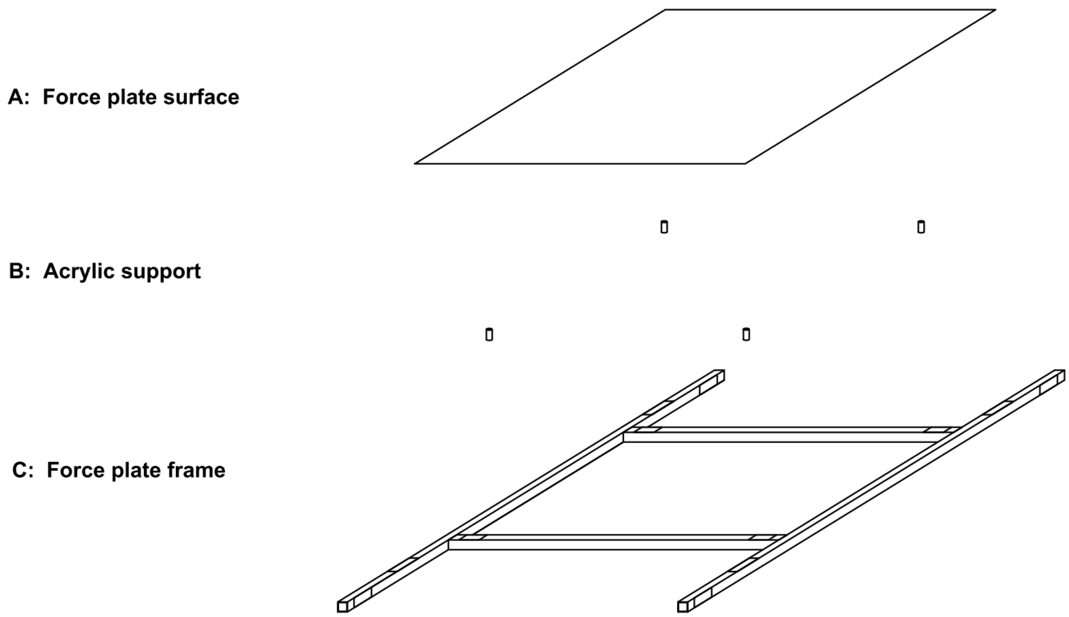


Figure 2.1: The components of the designed force plate

2.2 Calculation

2.2.1 Force plate surface dimension

The dimension of the force plate should be designed according to the requirements discussed in 2.1. A mature discoid cockroach is around 1.4-1.8 inches (35-45 mm) in length. The length of the force plate surface is designed to be 5 inches (127 mm) to span one entire stride length of the discoid cockroach. The width of the surface is designed according to the width of the climbing track. Cockroaches run with a gait that is mechanically similar to the bouncing gait [Full and Tu, 1990]. They use two tripods swinging from one to another along the moving direction to move forward. Another reason is that an appropriate dimension should be set for the short bridge beams that measure the fore-aft force so that the deflection of the spring blade elements can be clearly recorded by strain gauges. Thus the width of the climbing track, and of the force plate's surface is 4 inches (102 mm).

2.2.2 Force plate frame dimension

Figure 2.2 presents a schematic drawing of the force plate frame designed modified after previous design [Biewener, 1992,Goldman et al., 2006]. The performance characteristics and representative dimensions are shown in Table 2.1. The force transducing elements of the platform are composed of four hollow brass beams, which consist of two long side beams and two short bridge beams. The two short bridge beams support a stiff, light-weight panel that serves as the surface of the force platform. During the process of experiment, plywood, FR4 and carbon fiber were used for testing and the detailed results are given in the following section. Here, as the animal to be studied is cockroach, carbon fiber is chosen to be the surface material. The bridge beams and the surface carbon fiber panel are connected by four cylindrical acrylic blocks.

2.2.3 Natrual frequency

Before the fabrication of the force plate, the natural frequency of the force plate frame should be decided. It is shown that the force plate needs around 200 Hz of unloaded natural frequency to guarantee the safety of recording the primary signals.

According to the mechanical properties of the beam metal and the maximum load, equations of beam theory are used to calculate the appropriate dimension of the spring blade elements [Young, 1989]. For a maximum force P, spring blade thickness can be

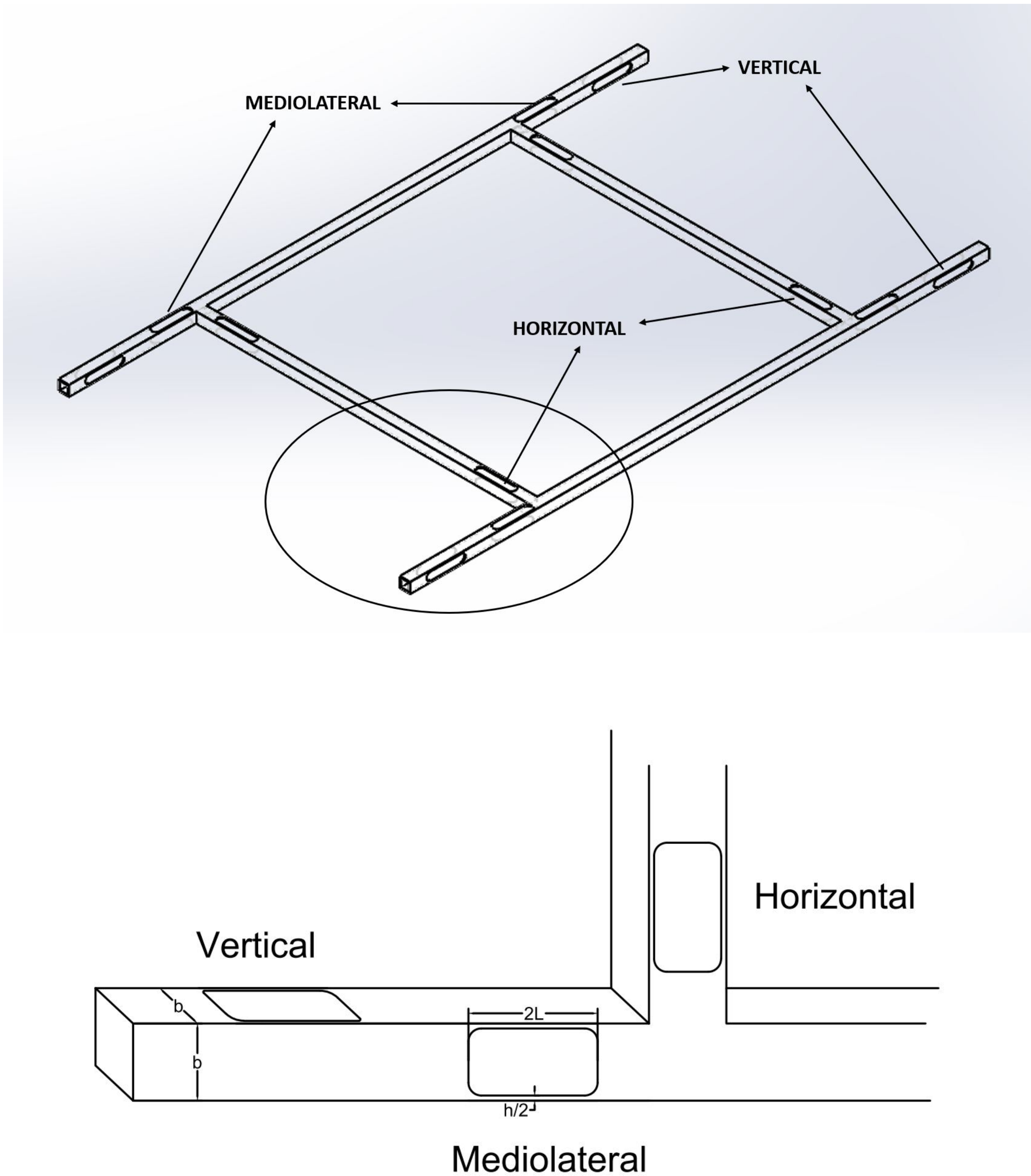


Figure 2.2: Schematic drawing of the force plate design

determined by

$$h = \sqrt{\frac{6PL}{bS}} \tag{2.1}$$

where L is the length of the cantilever formed by half of the balde, b is the spring blade width, and S is the yield strength.

The natural frequency of vibration is determined by the weight of the suspended part of the force platform and the stiffness of the spring blade elements. Thus the natural frequency can be determined once the force plate frame and the surface's dimensions are known. The self-loaded natural frequency of the force platform is decided by

$$f_n = \frac{0.5}{\sqrt{2D}} \tag{2.2}$$

where D is the deflection and can be determined by

$$D = \frac{4WL^3}{Ebh^3} \tag{2.3}$$

where W is the weight of the suspended part and E is the elastic modulus of the beam metal.

By plugging in the value of dimensions into equation (1)-(3), a plot of self-loaded natural frequency versus the half length of the cantilever formed by spring blade is shown. From the figure above, the half length of the spring blade should be less than 7.8 mm to design a force plate with the natural frequency higher than 140 Hz so that it is well above all the single frequency of interest. The vibration of the force platform itself cannot be neglected during experiments, so the natural frequency of the force plate should be higher than 200 Hz. Then we can remove the oscillation frequency of the force plate by using a butterworth filter at 180 Hz.

Table 2.1: Specifications and representative characteristics of brass beams

Animal weight (N)	0.03
Peak load, P (N)	0.3
Plate dimensions	
length (inch)	7
width (inch)	5
Surface thickness (mm)	0.15
Material	carbon fiber
Beam material	brass
Outside width (inch)	0.125
Outside length (inch)	0.125
Stiffness, E (Gpa)	105
Yield strength (Mpa)	105
Density (kg/m^3)	1 000
Beam dimensions	
b (mm)	3.18
L (mm)	6
h (mm)	0.071 12

2.2.4 Finite element analysis

Some FEA simulations have been done to analyze the deflection of the spring blade elements of the force plate during the experiment. Given the specific dimensions of the force plate and the spring blade elements, we can analyze the deformation by adding the designed load to the force plate in three axis respectively.

When adding the load of 0.03 N, the average weight of a cockroach, the distance of the vertical spring blade deflection is $4.216 \times 10^{-}3$ mm. The counterparts of the mediolateral and fore-aft channel are $3.095 \times 10^{-}3$ mm and $2.957 \times 10^{-}3$ mm. When deformation happens, Figure 2.4 shows that the largest displacement and strain are at the cantilever formed by half of the spring blade where the strain gauges should be mounted to.

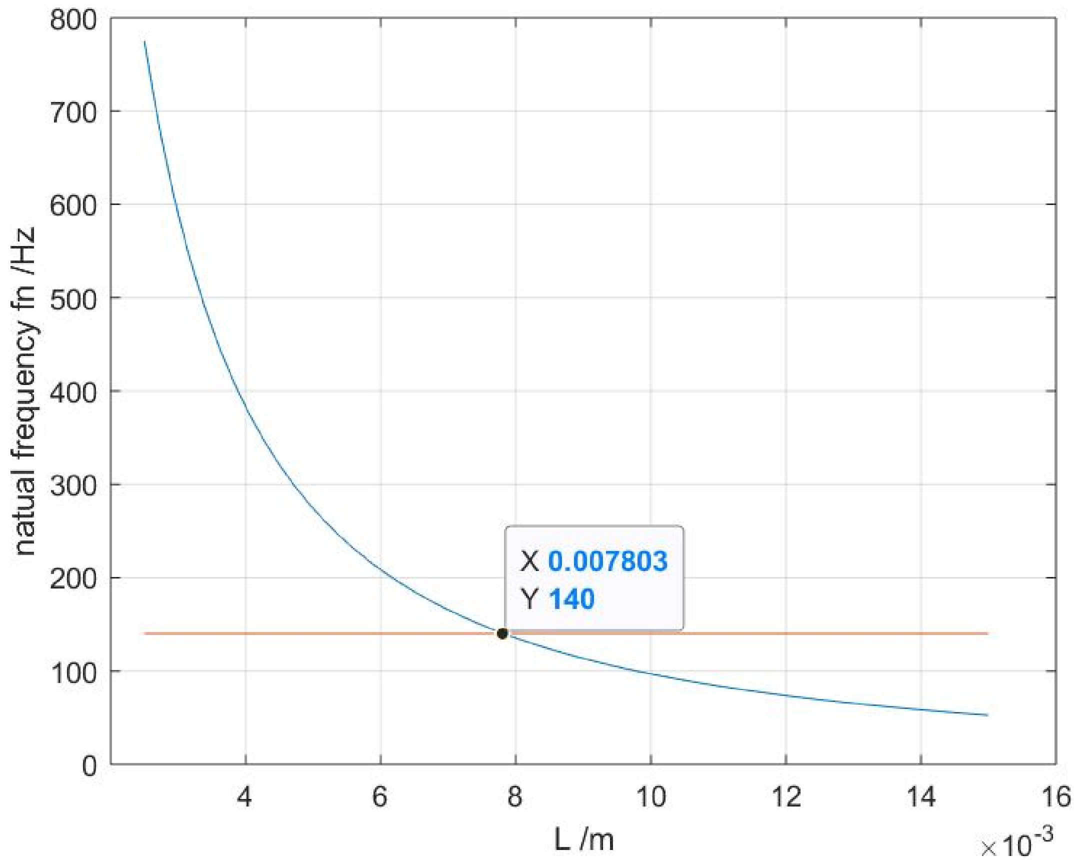


Figure 2.3: Self-loaded natural frequency versus the length of half spring blade

2.3 Material

2.3.1 Force plate frame material

The basic idea to design this force plate includes independently measuring the forces in each of the three channels by collecting the voltage signal of strain gauges mounted to the spring blade elements of the four brass beams.

For the force plate frame, hollow brass tube (Mcmaster Corp.) is used here to fabricate the four brass beams. The Ultra-Formable 260 Brass Rectangular Tube works well in this project because we need to cut or mill some slots on the surface of the brass tube. The wall thickness of this brass tube is 0.014 inch (0.3556 mm), which is also the

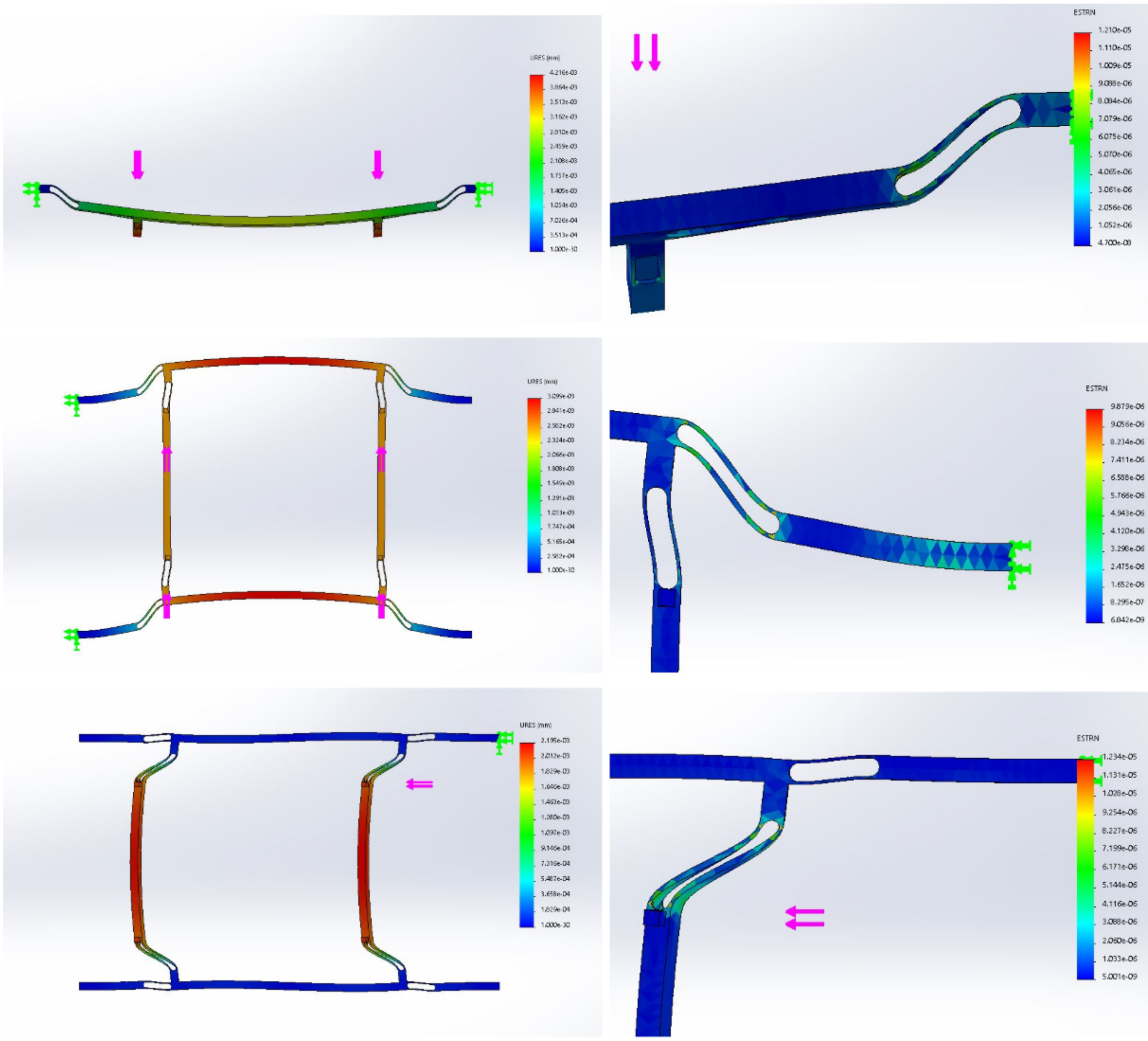


Figure 2.4: FEA simulation results.

thickness of spring blades.

2.3.2 Force plate surface material

The choice of material for the force plate surface is important as it relates to the natural frequency of the whole force platform. During the testing process, three kinds of material have been used to fabricate the surface, which are plywood, FR4 and carbon fiber. To ensure the sufficient natural frequency of the force platform, the surface should be as

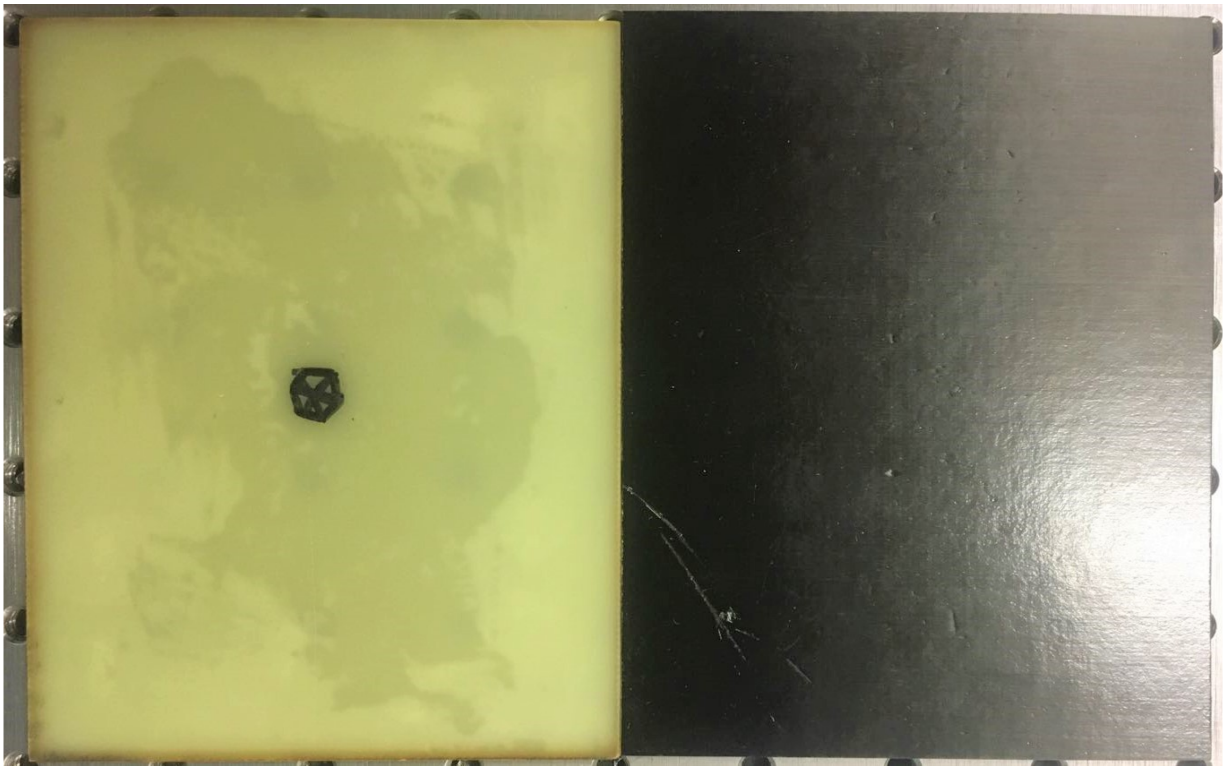


Figure 2.5: Force plate made with FR4 and carbon fiber

light-weight as possible, but at the same time it should be stiff enough or the fluctuation of the surface will add noise to the signal measurement.

The plywood is not a desirable material for the surface since a very thin layer of plywood is not accessible. Thus the kind that is usually used in lab is rather heavy than the other materials.

FR4 is a composite material composed of woven fiberglass cloth with an epoxy resin binder. It is pretty stiff in one direction and quite bendy in another perpendicular direction. The force plate surface of FR4 version laminates two layers of FR4 which are perpendicular in direction so that the surface would have equal stiffness in all directions. The force plate made with FR4 is definitely thinner than the plywood version. However, it is still rather heavy compared to carbon fiber.

Carbon fiber works well for its extremely light weight and stiffness. In this study, carbon fiber panel is made by laminating 12 layers of carbon fiber sheet. The thickness of the final surface is about 0.15 mm with weight of just 6 g.

2.4 Fabrication

2.4.1 Equipment used

The major equipment used in fabrication process was:

- ☐ Othermill
- ☐ Glowforge laser machine
- ☐ Hydraulic press

The other mill is a desktop milling machine which is mostly used for PCB milling and engraving work. Here it is used to mill the slots which form the spring blade elements. The dimension of the brass tubes that are used for beams is 3.18 mm, which is not so convenient to mill the slots on large milling machines. Using Othermill to cut the slot is efficient and effective. The Glowforge laser machine has been used to laser cut the materials like FR4 and acrylic.

2.4.2 Fabrication process

To cut the slots for the spring blade elements, 1/16" flat end mill bit is used here to engrave the brass tube. According to the material library of the other mill, the feed rate, plunge rate are chosen at 200 mm/min and 16.66 mm/min respectively. The spindle speed is 12,000 RPM and the max pass depth is 0.07 mm. Since the wall thickness of the brass tube is 0.3556 mm according to section 2.2, we need to engrave the brass tube multiple times to cut through the surface of the tube. The milling slots are presented in Figure 2.8.

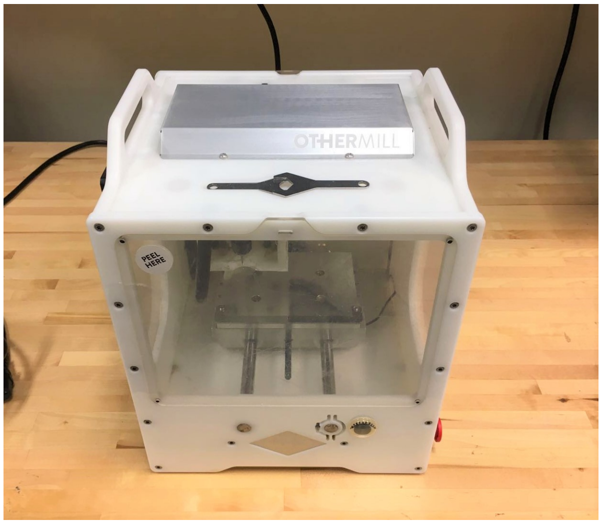


Figure 2.6: Othermill for cutting spring blade slots

Figure 2.7: Glowforge laser cut

The spring blade elements for vertical and lateral force are at two ends of the long brass beams and the counterparts for fore-aft force are on two bridge brass beams.

After cutting the slots, the four brass beams need to be soldered together to form the force plate frame. Tin solder wire will work here since the brass tube cannot undertake the high temperature and tin soldering can provide sufficient force in this study. The soldered force plate is shown in Figure 2.9.

To fabricate the force plate surface, 12 layers of carbon fiber sheet were used for lamination. 12 layers consist of carbon fiber sheet in 6 directions so that the final carbon fiber panel will be stiff along all the directions. By compressing and heating the carbon fiber by using hydraulic press, we get the 12 layer carbon fiber sheet. Cutting the carbon

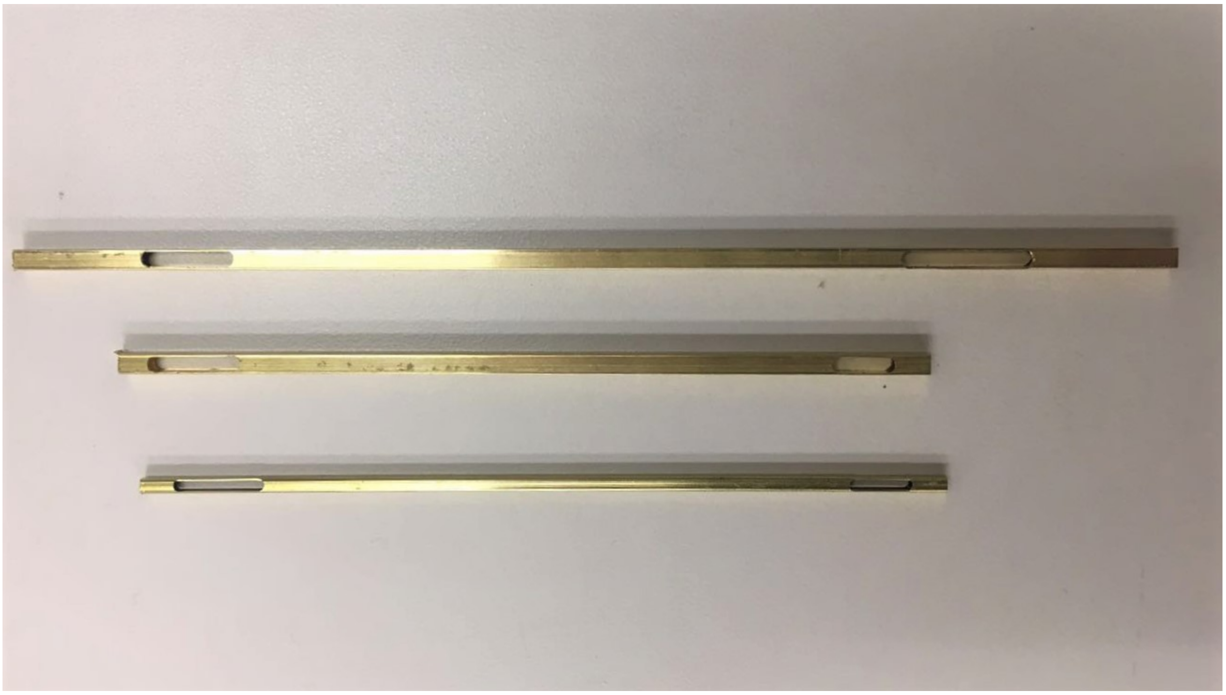


Figure 2.8: Brass beams with slots of different sizes

fiber sheet into a 4×5 inches rectangle and the surface is done. The compressed carbon fiber panel is shown in Figure 2.10.

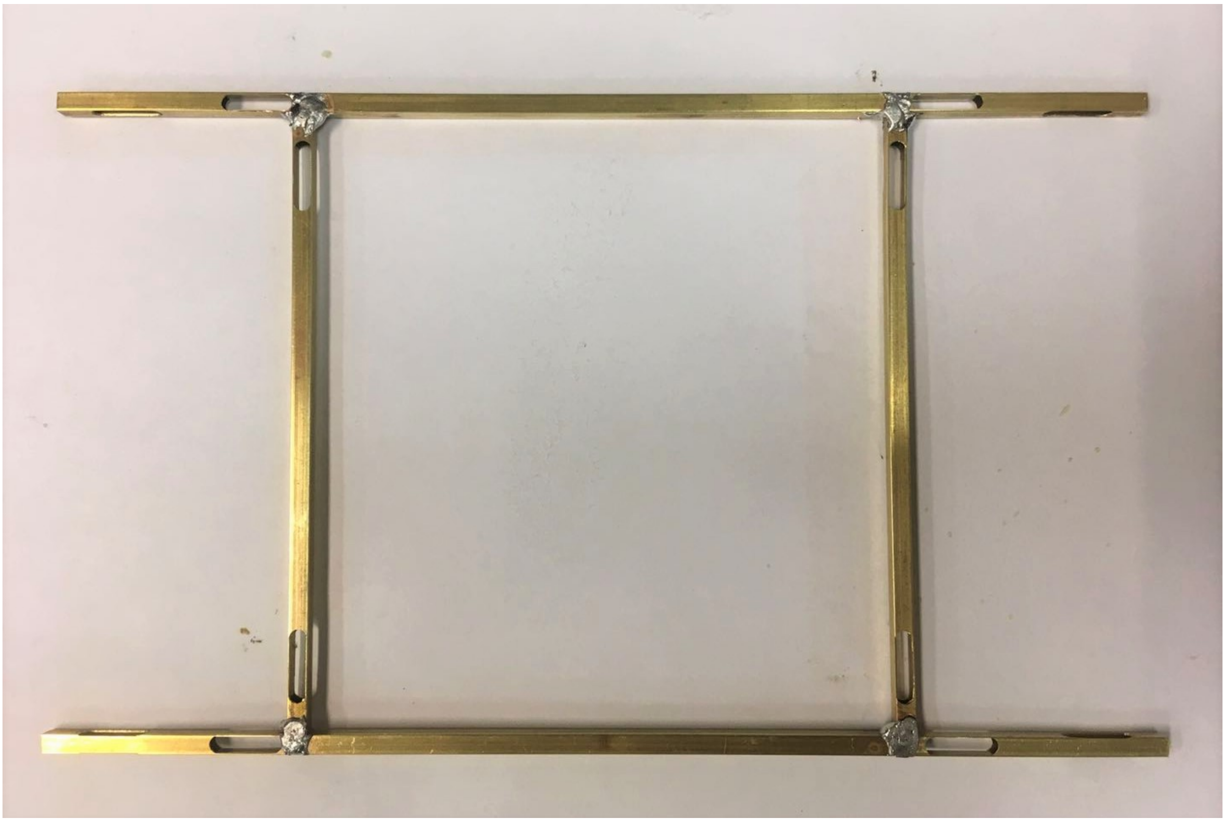


Figure 2.9: The soldered force plate frame

Figure 2.10: Compressed carbon fiber panel

Chapter 3

Strain-gauge and electronic considerations

3.1 Strain-gauge

3.1.1 Selection of strain-gauge

There are multiple choices of strain gauges. Either metal foil resistive strain gauge or semiconductor strain gauge can be used here for the force transducing based on deflections of the spring blade elements.

A normal foil resistive strain gauge consists of an insulating flexible backing which supports a metallic foil pattern. The advantage of the resistive strain gauge is that it is easy to use and have good temperature stability, but the disadvantage of the resistive strain gauge is that it is less sensitive to the deflection of the spring blade elements, which means lower voltage output per strain.

While semiconductor strain gauges usually have much larger gauge factor than foil ones. Thus semiconductor strain gauges are more sensitive than foil strain gauges, but they are also more sensitive to temperature change and more fragile than the foil ones. The cost of semiconductor strain gauge is comparatively high.

In this study, considering the cost of the whole project and the durability of the force platform, metal foil strain gauges are chosen as force transducing elements. We use the pre-wired linear gauge KFH-3-120-C1-11L1M2R (OMEGA Corp.), which is convenient to use since there is no soldering at the measuring point.

Figure 3.1: Pre-wired linear gauge KFH-3-120-C1-11L1M2R (OMEGA Corp.)

3.1.2 Strain-gauge installation

To achieve the maximum sensitivity of the force platform within the limits of the metal foil strain gauge, the strain gauge should be mounted to the first half of the cantilever formed by the blade according to the deformation of the spring blade elements. The maximum deflection happens on the one-half of the blade, while the middle part is rather flat according to Figure 3.2.

The first step of the installation is to clean the surface of the spring blade. Using sandpaper with roughness of 400 to sand the mounting surface can remove the stain and oxide layer. Then clean paper towel dipped in water or alcohol is used to wipe out the dust.

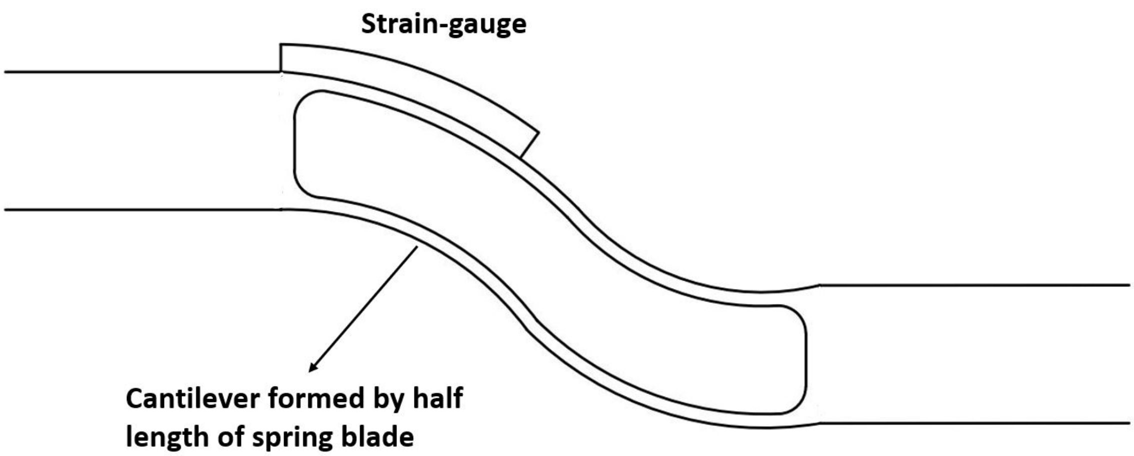


Figure 3.2: Strain-gauge installation location

Before applying the strain gauge, use a paper towel to dry the surface. After cleaning the mounting surface, now we can place the strain gauge at the mounting surface and use a piece of transparent tape to locate the strain gauge. Then lift up the tape from the side with no wire, apply some epoxy and recover the tape. Heat and cure for at least one minute and uncover the transparent tape, and the strain gauge is mounted well. Lead wires of strain gauges should be arranged via a strain relief connector mounted adjacent to each strain gauge.

3.2 Electronic consideration

3.2.1 Electric circuit

The strain gauges are configured as a full-bridge for input to a conditioning Wheatstone bridge amplifier (Figure 3.3). The strain gauges for vertical force measurement should be wired as a whole Wheatstone bridge separately on the front and rear brass beams so the force platform can provide independent force measurement at the front and the rear side of the force plate. However, strain gauges of the medio-lateral and fore-aft force measurement should be grouped into a single full bridge circuit, which sums forces over the entire force plate. A full bridge can help remove the temperature drifting.

To balance the wheatstone bridge, a sliding resistor is used in the circuit. By tuning the resistor's resistance, the output voltage can be balanced to zero. An amplifier is also needed here to amplify the output voltage as the forces applied to the force platform are in small scale.

3.2.2 Electronic components

The amplifier used in the electric circuit is the INA125 (Texas Instrument Corp.). INA125 is a low power, high accuracy instrumentation amplifier with a precise voltage reference, which provides complete bridge excitation and precision differential amplification on a single integrated circuit. A single external resistor can set the gain from 4 to 10 000. It also has very low offset voltage and low offset drift and operates on dual ($\pm$ 15 V) supplies. The voltage reference is externally adjustable with pin selection, allowing use with a variety of transducers. For the two vertical force measurement circuit, four strain gauges with resistance of 120 Ω are used in the bridge, so the reference voltage is chosen according to the resistance of the bridge as 1.25 V. While for the mediolateral and the fore-aft circuits, eight strain gauges with resistance of 120 Ω are used in the bridge separately, so the reference voltage is chosen as 2.5 V. As for the gain of the amplifier, here an external resistor of 6 Ω is used to tune the gain to its highest value 10 000.

All the electronic components are soldered to the circuit board to avoid the fluctuation and drift of the strain gauge. In addition to that, it is also convenient to integrated them all under the force plate surface.

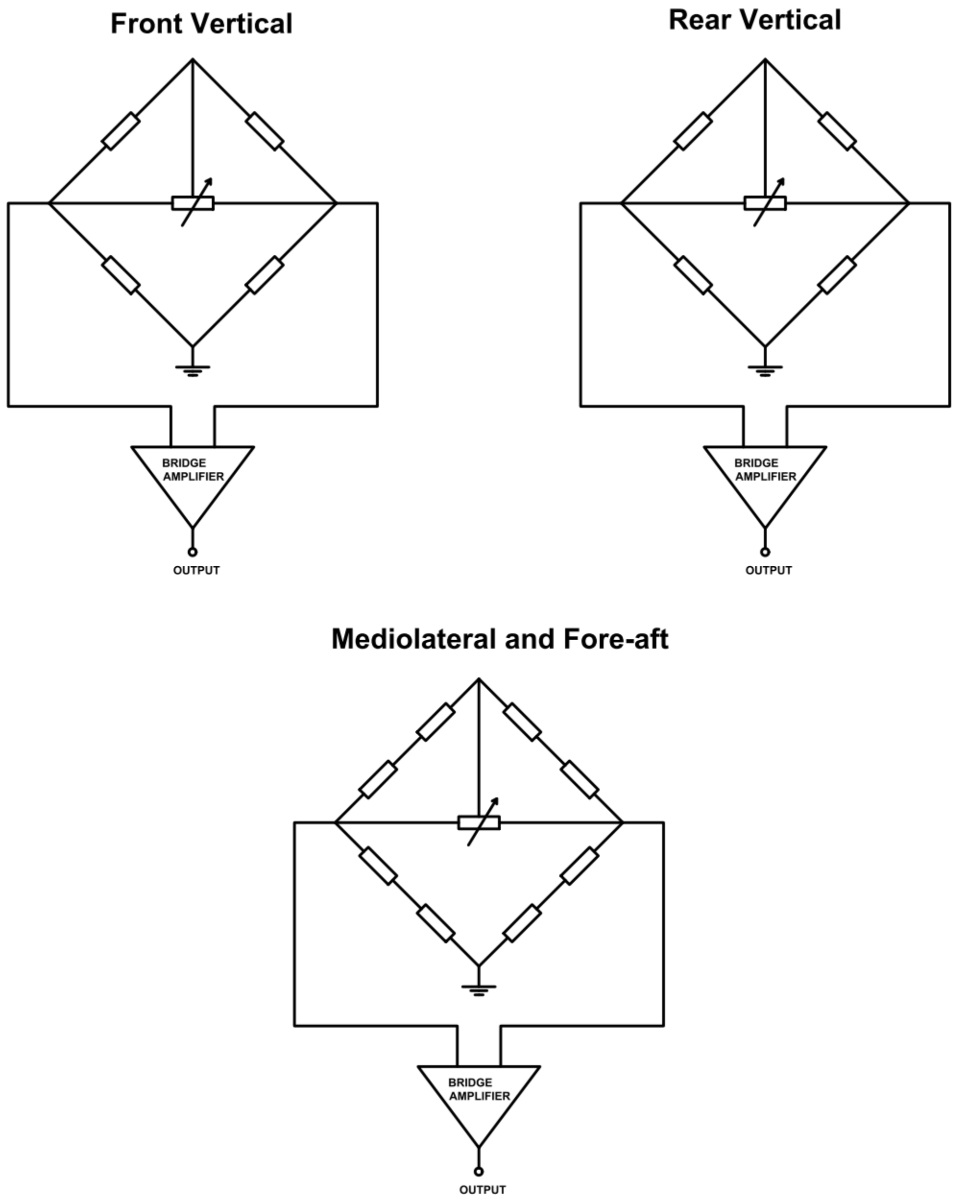


Figure 3.3: Force plate bridges configurations

Chapter 4

Design of the experiment apparatus and force plate calibration

4.1 Setup

Figure 4.1 shows the whole setup of the cockroach incline climbing experiment, which consists of the force platform, high speed camera, DAQ and computer. In this section, the components of the force platform are introduced.

4.1.1 Running trackway

The running trackway of the force platform consists of the 80/20 framework and the acrylic substrate. The dimension of the running track is designed to be 20 inches in length and 5 inches in width. The force sensor plate is mounted in the middle of the running track, and the surface of the force plate is at the same height as the running track. There are small gaps of 1mm between the edges of the force plate surface and the running track to avoid confliction.

To avoid sliding problem when studying cockroach, sand papers or rubber will be

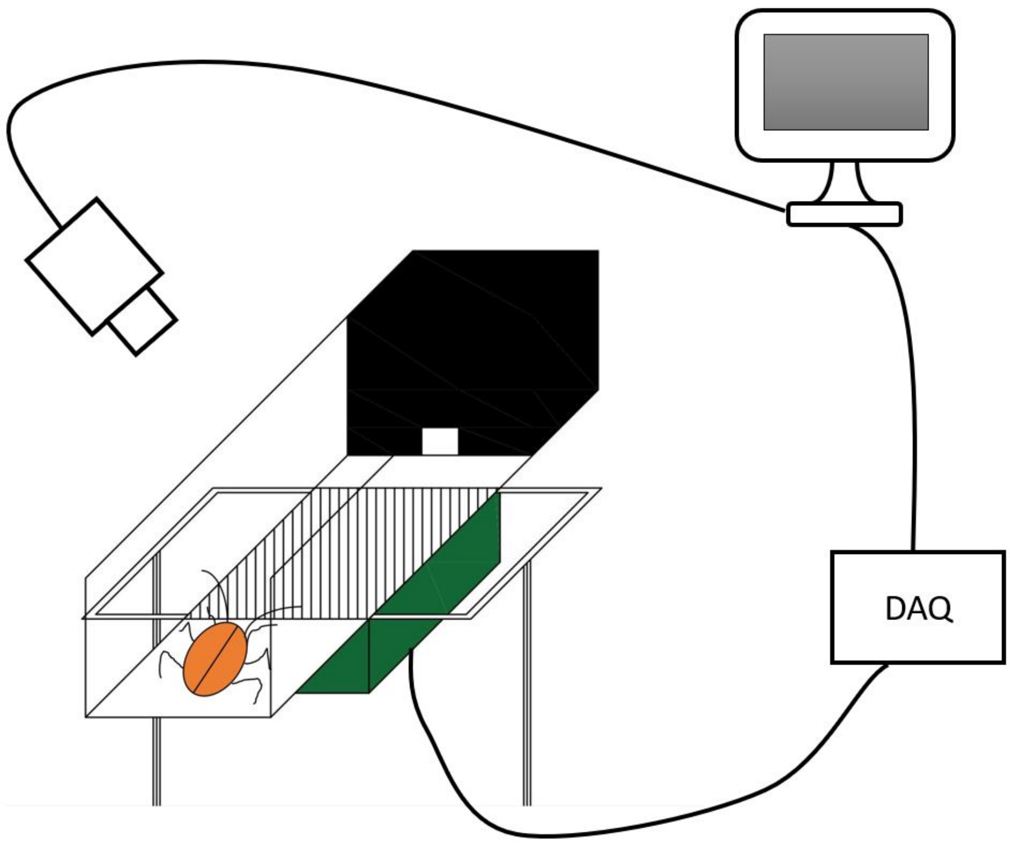


Figure 4.1: The whole setup

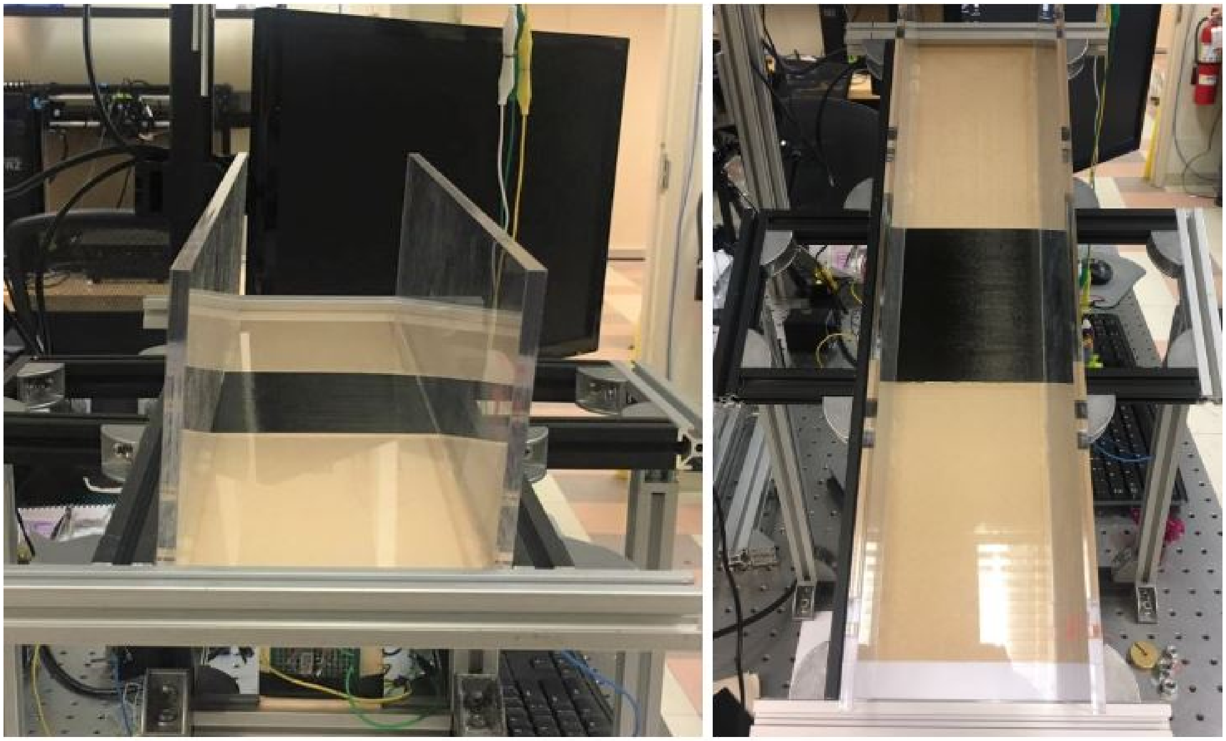


Figure 4.2: Running trackway

applied to the surface of the running track. There are transparent acrylic walls on the two sides of the running track to constraint the moving direction of the cockroach, at the same time the cockroach can also be recorded by camera through acrylic walls.

As cockroaches do not like bright place, a dark room made with cardboard is set at the end of the running track to attract them to climb through the running track and the force plate surface.

4.1.2 Strain-gauge tree

A total of 24 strain gauges have been used in the force plate design, so the arrangement of the wires and the circuit boards could be a problem. In this project, the four circuit boards are mounted into a 80/20 frame which is installed right under the running trackway.

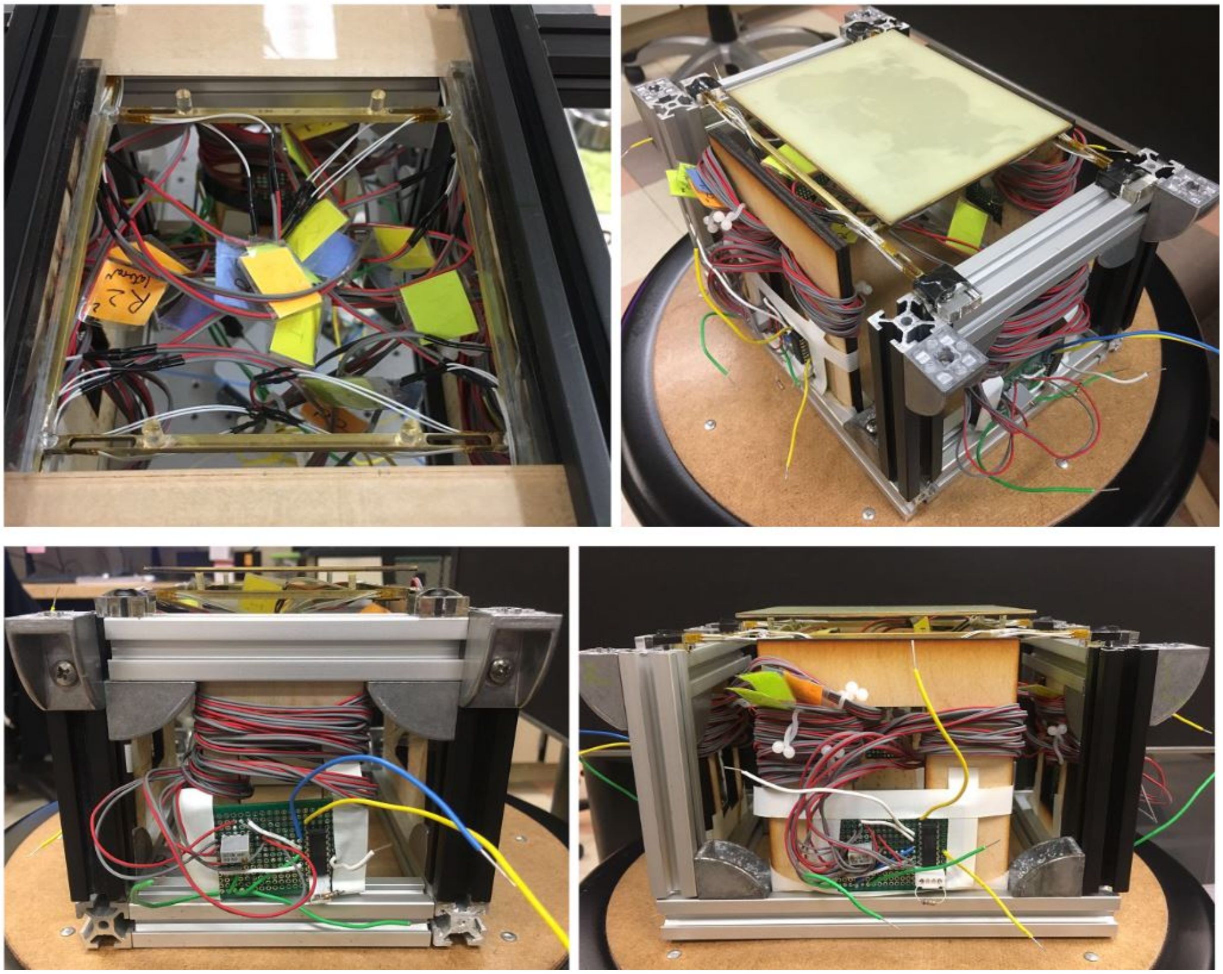


Figure 4.3: Strain-gauge tree

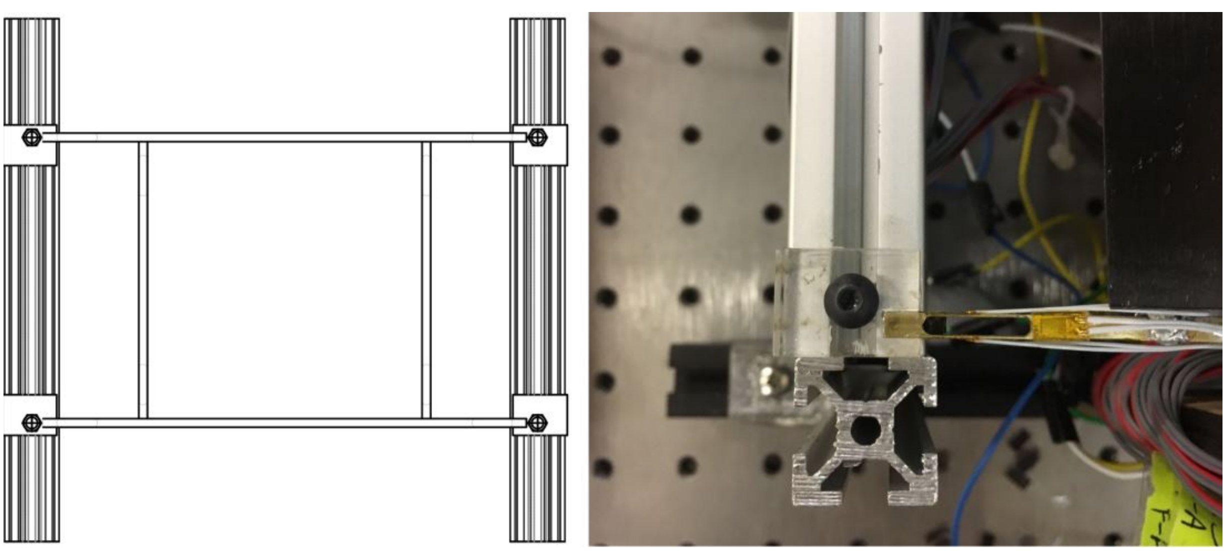


Figure 4.4: Force plate constraints

The force plate frame is fixed on the 80/20 frame by laser cut acrylic parts. By constraining the four edges of the force plate, the spring blade on the brass beams will deform if any load is applied to the surface.

4.1.3 Tilting device

As one of the targets of designing this force platform is to study the locomotion of cockroaches climbing through inclined surfaces with different angles, a tilting device is needed in the setup of the force platform. Two 80/20-compatible pivots are used to achieve the tilting function.

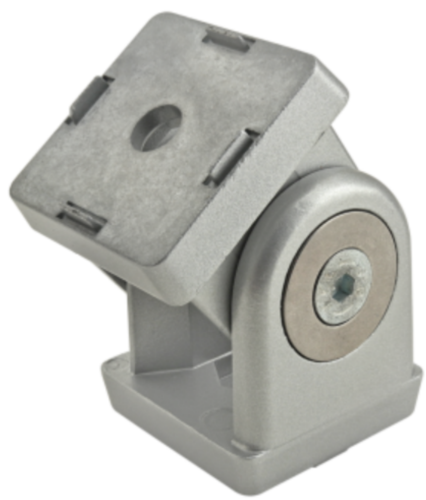


Figure 4.5: 80/20-compatible pivots (Mcmaster Corp.)

With the tilting device, the running track can be set from the horizontal position to a vertical position (0° to 90°) continuously and smoothly.

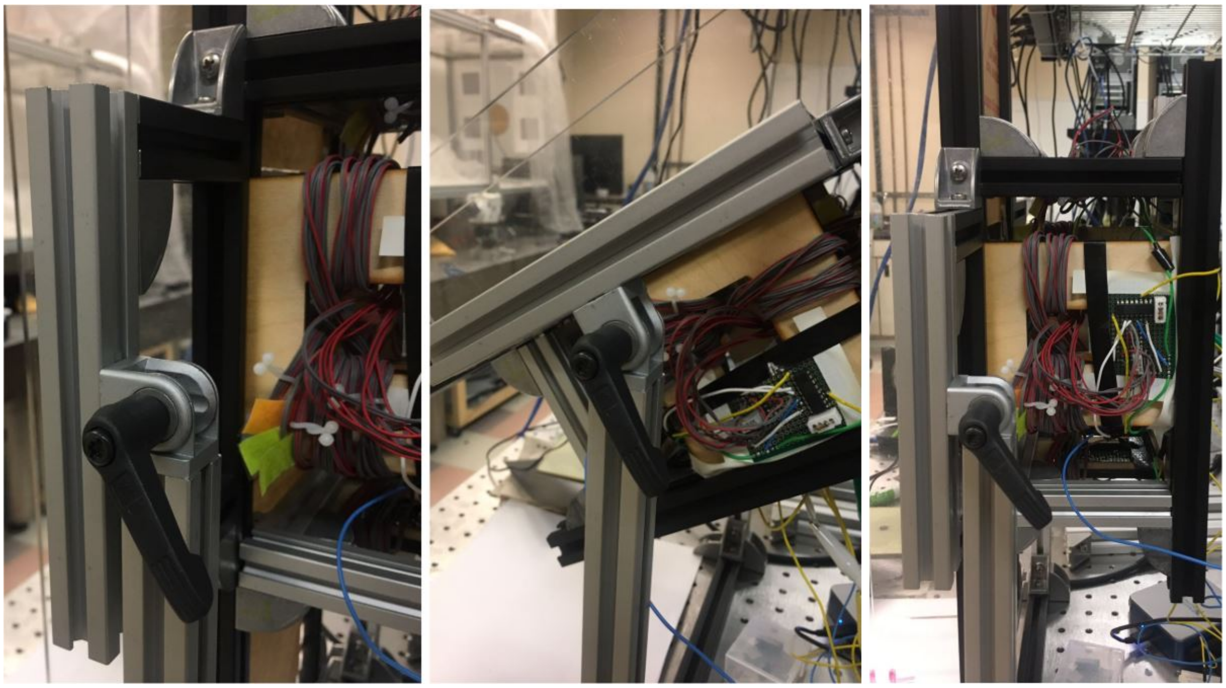


Figure 4.6: The tilting device made with 80/20-compatible pivots

4.2 Calibration

A calibration of the force platform should be done to test the integrity of the strain gauges, the electronic components and of any changes could happen to the sensitivity that may occur during its use in the previous experiment. The following contents provide a detailed calibration process and tests of the performance characteristics of the force platform.

4.2.1 Calibration of the four force channels

In order to calibrate four circuits, a calibrated set of weights is used.

To calibrate the vertical force, place a weight that is equal or greater than the maximum expected that is to be recorded at the center of the force plate surface and adjust the external resistor of two circuit so that a clear output can be recorded. In this study, the highest gain is chosen for the circuit to record the output. Record the front and rear vertical force outputs by using a DAQ as increasing known weights at the center of the force plate.

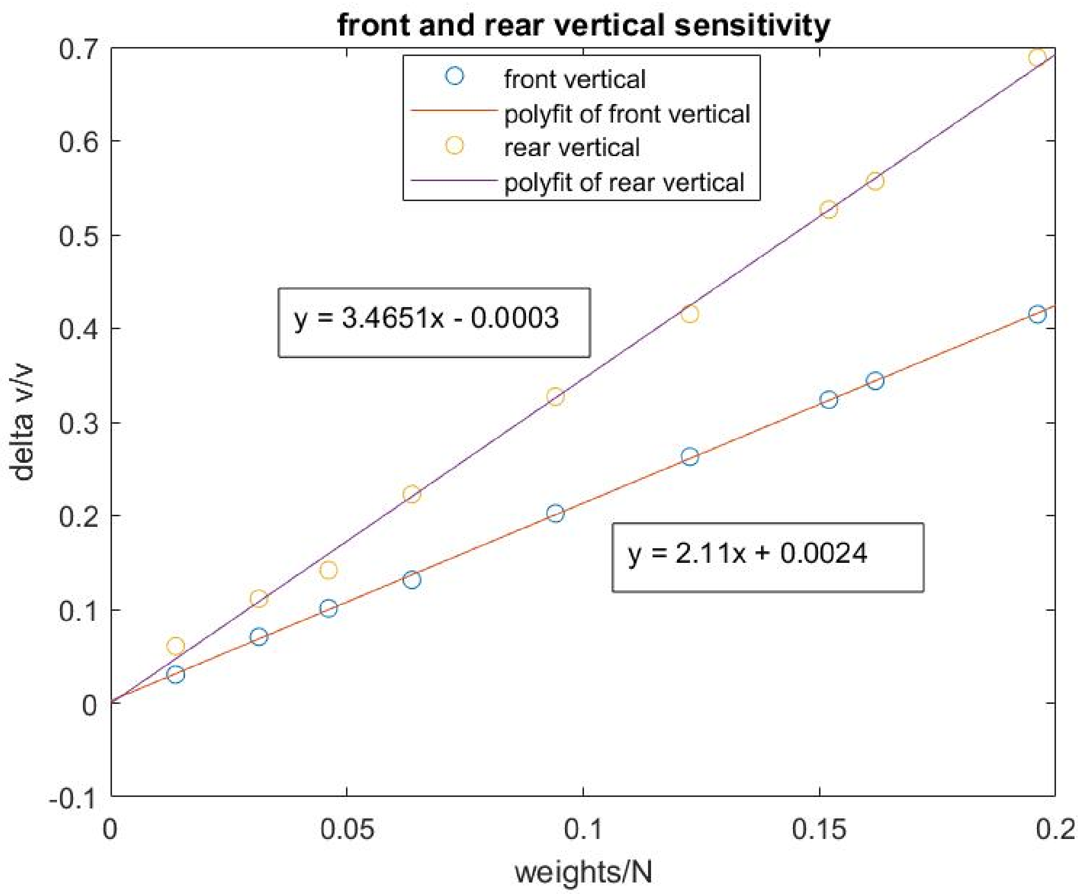
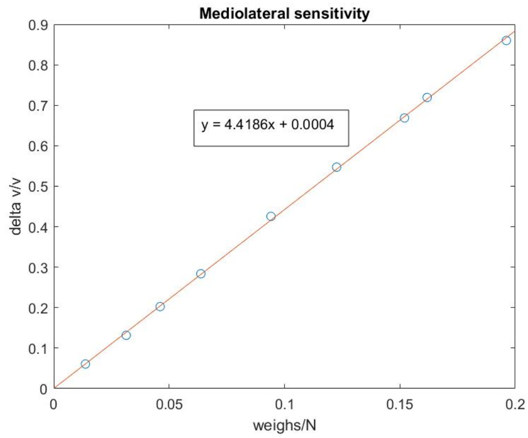
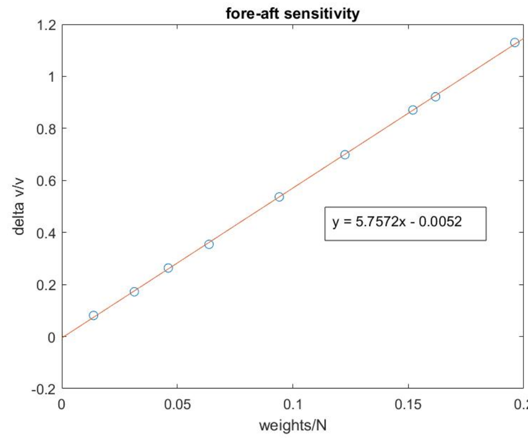


Figure 4.7: Front and rear vertical sensitivity. The front vertical channel's sensitivity is 3.4651 V/N and the rear vertical channel's sensitivity is 2.11 V/N.

To calibrate mediolateral and fore-aft force, the approach of a frictionless pulley can be used here. A nylon cord is taped to the surface of the force plate and passes through a frictionless pulley that is placed at the same height as the force plate surface. Record the force outputs as gradually increase the known weights that are attached to the end of the nylon cord.



(a)



(b)

Figure 4.8: Mediolateral and fore-aft force channel sensitivity. The mediolateral channel's sensitivity is 4.4186 V/N and the fore-aft channel's sensitivity is 5.7572 V/N.

4.2.2 Sensitivity to the position variation

Sensitivity to the position variation is determined by placing a known weight at different locations of the force plate surface and record the force outputs of the front and rear vertical force channels.

The typical variation due to the position of applied force should be less than 3 %, which happens at the extremes of the plate's surface. Figure 4.9 shows that the result meets the requirement.

4.2.3 Cross-talk between channels

One of the reasons of doing calibration is to solve the relation between the voltage signal and the force decomposed by the force plate. The transfer matrix between voltage and force will be a diagonal matrix if there is no cross-talk between any channel, so the

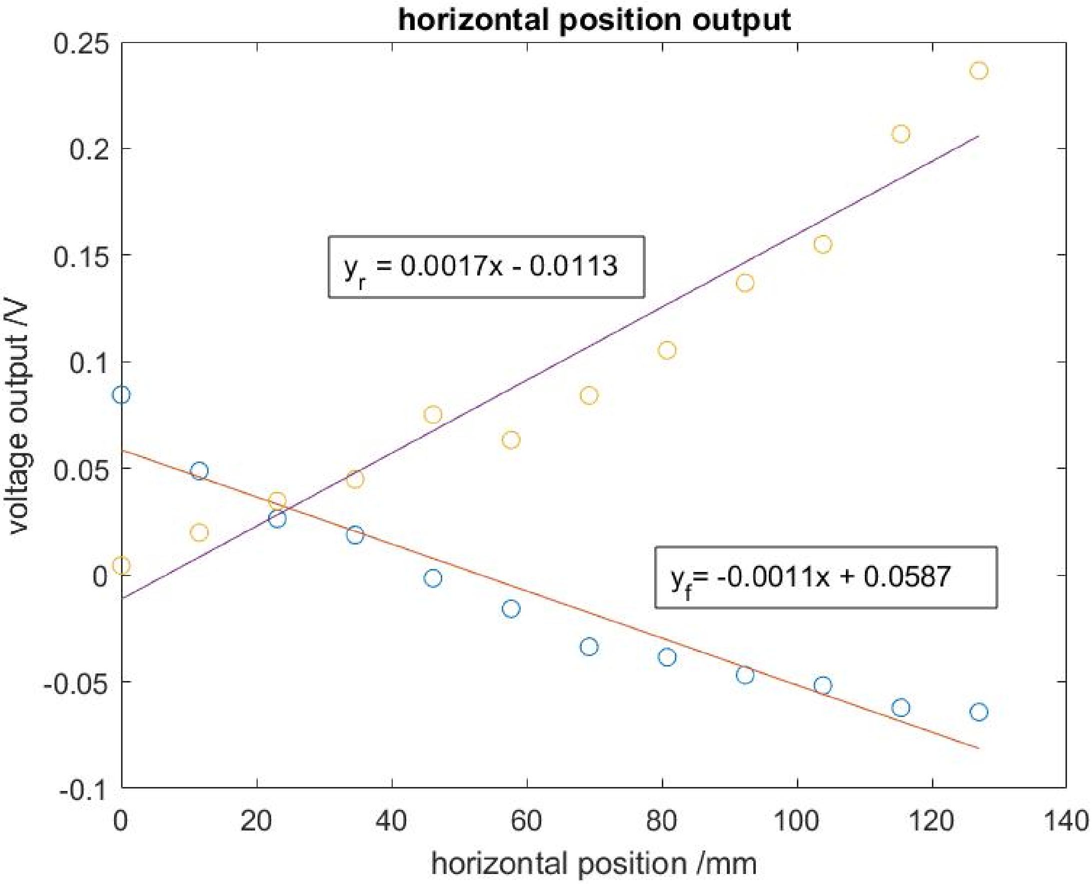


Figure 4.9: Front and rear vertical position sensitivity. The front vertical channel's sensitivity is 0.0011 V/N and the rear vertical channel's sensitivity is 0.0017 V/N.

relationship between the two can be represented by

$$T \star \begin{bmatrix} F_{fv} \\ F_{rv} \\ F_{ml} \\ F_{fa} \end{bmatrix} = \begin{bmatrix} V_{fv} \\ V_{rv} \\ V_{ml} \\ V_{fa} \end{bmatrix} \tag{4.1}$$

where $T = \begin{bmatrix} 2.11 & 0 & 0 & 0 \\ 0 & 3.4654 & 0 & 0 \\ 0 & 0 & 4.4186 & 0 \\ 0 & 0 & 0 & 5.7572 \end{bmatrix}$ according to the sensitivities of four channels.

However there is cross-talk between different channels in practical, so the off-diagonal elements might not be zero. The cross talk between channels is determined by recording the mediolateral and fore-aft force channels when adding known weights to the vertical channels. For the other two channels, just repeat the procedures. The cross-talk between the vertical channel and other two channels is 0 when adding loads to the vertical axis. The cross-talk shown when adding loads to mediolateral and fore-aft channel is given in the following plots. The cross-talk between vertical channel, mediolateral channel and fore-aft channel was less than 5 % for all channels.

After solving the cross-talk between all the channels, now the transfer matrix between voltage and force can be revised as $T = \begin{bmatrix} 2.11 & 0 & 0 & 0 \\ 0 & 3.4654 & 0 & 0 \\ 0.1559 & 0.0808 & 4.4186 & 0 \\ 0.4611 & 0.6423 & 0 & 5.7572 \end{bmatrix}$.

Since the voltage signal is the output of the experiment, the transfer matrix between voltage signal and force can be solved by multiplying the inverse of T to equation 4.1

$$T^{-1} \star T \star \begin{bmatrix} F_{fv} \\ F_{rv} \\ F_{ml} \\ F_{fa} \end{bmatrix} = T^{-1} \star \begin{bmatrix} V_{fv} \\ V_{rv} \\ V_{ml} \\ V_{fa} \end{bmatrix} \tag{4.2}$$

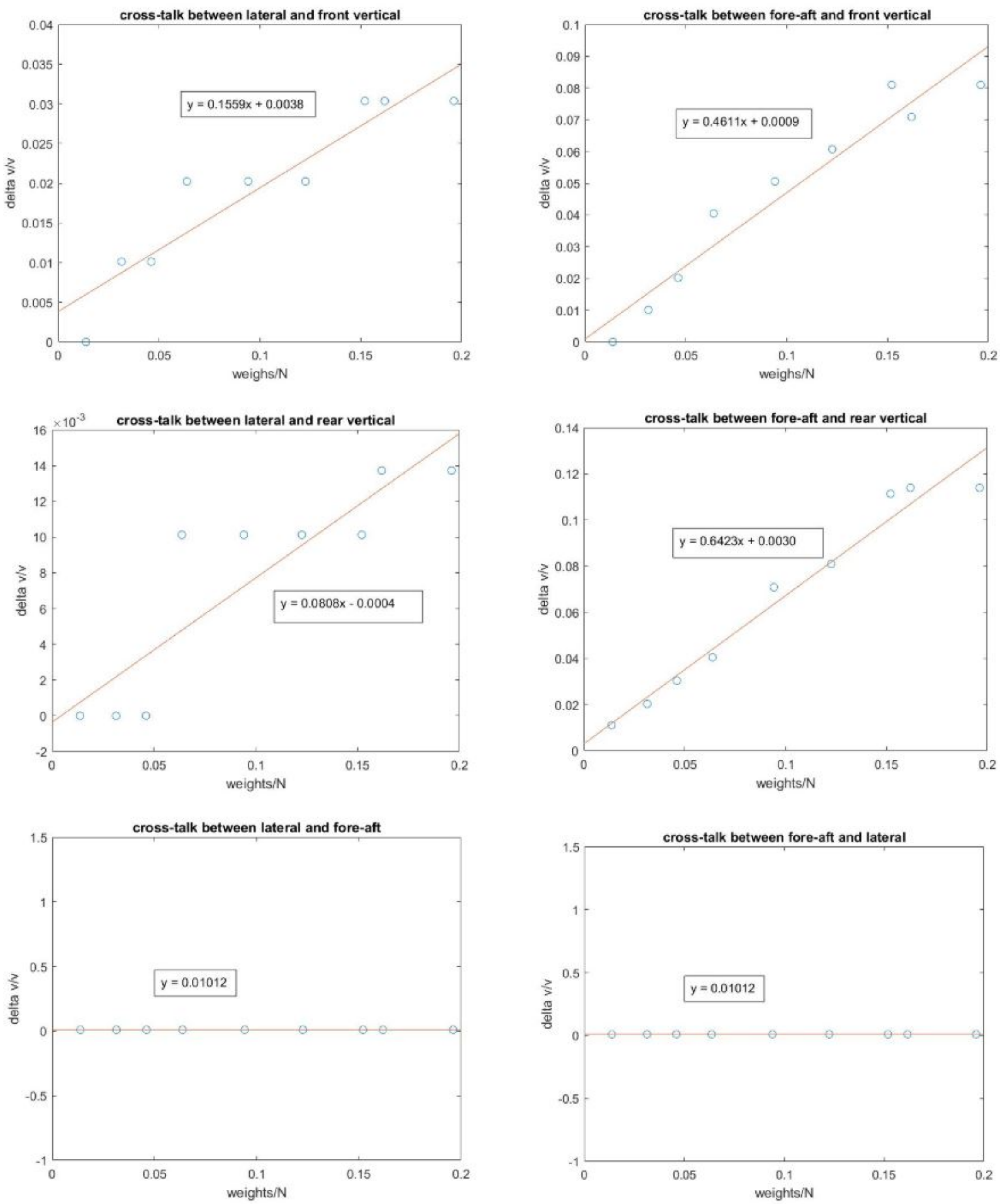


Figure 4.10: Cross-talk between different channels.

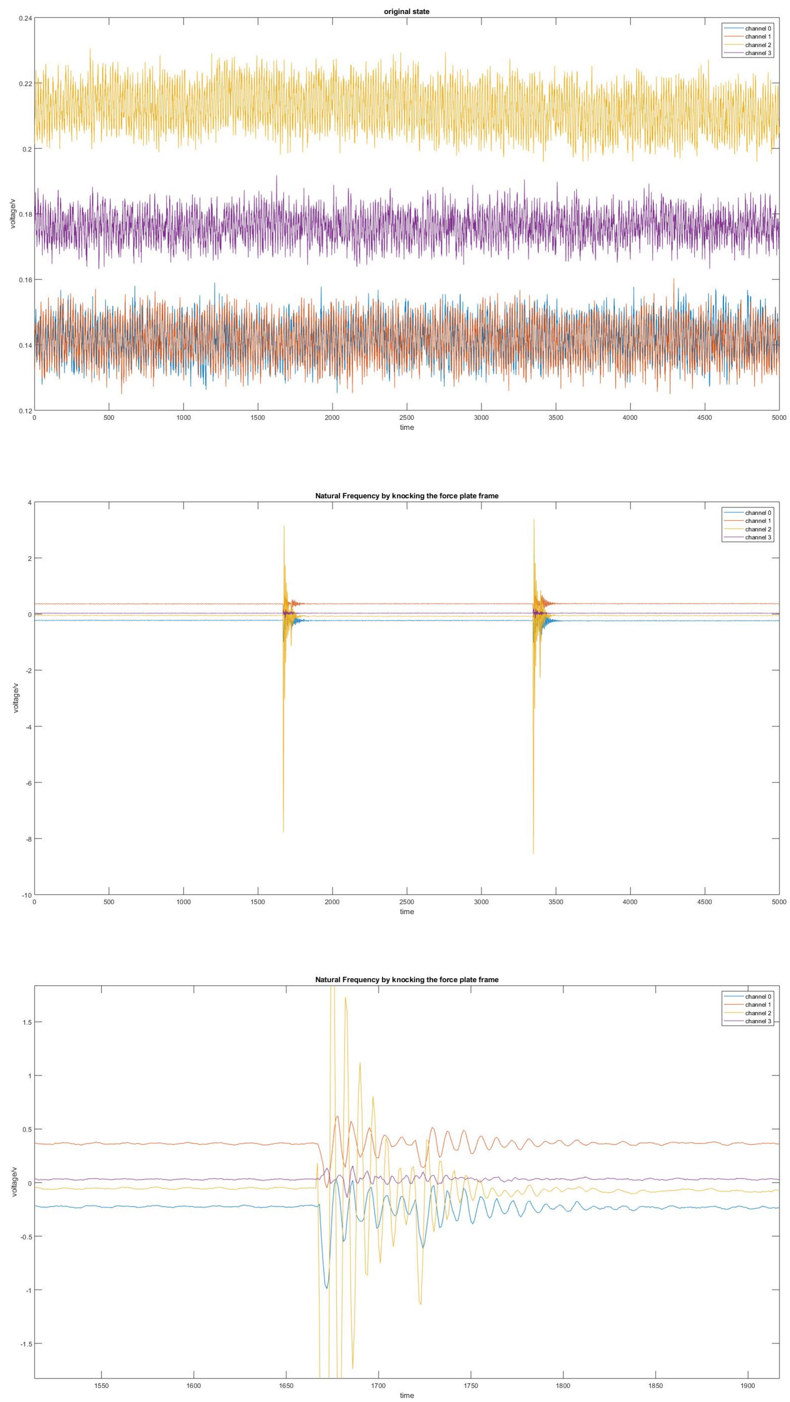


Figure 4.11: The original and ringing states of the force platform

and then we get $T^{-1} = \begin{bmatrix} 0.4739 & 0 & 0 & 0 \\ 0 & 0.2886 & 0 & 0 \\ -0.0167 & -0.0053 & 0.2263 & 0 \\ -0.0380 & -0.0322 & 0 & 0.1737 \end{bmatrix}$.

4.2.4 Force platform natural frequency

The natural frequency of the force platform is important for the data acquisition. A sufficiently high natural frequency is needed so that the primary signals can be recorded faithfully. To acquire the natural frequency of the force platform, simply strike the force plate with a metal bar, which will cause the force platform to vibrate. A high frequency ringing superimposed on the primary signal will display on each force channel. By doing the experiment multiple times and computing the average value, the natural frequency of the force platform can be determined.

According to the average value of 10 times striking, the natural frequencies of the mediolateral and fore-aft force channel are around 200 Hz, while the vertical force channels got natural frequencies of around 195 Hz.

4.3 Hexbug experiment

To test the calibrated force platform, here a hexbug (from HEXBUG Corp.) is used to do the running and climbing experiment. The hexbug toy weights 18.5 g, which is less than the maximum load of the force platform. Let the hexbug run through the whole track multiple times at each inclined angle. However the hexbug lacks ability in climbing the inclined surface, so the experiments were mainly done within the range of 0°-15°.

Set the angle of the running track to 0° and let the hexbug climb through the force plate surface. Tilt the running track to 15° and rebalance all four channels before

Figure 4.12: Hexbug used in experiments

start experiments since the weight of force plate itself will add load to the spring blades, especially for the fore-aft channel.

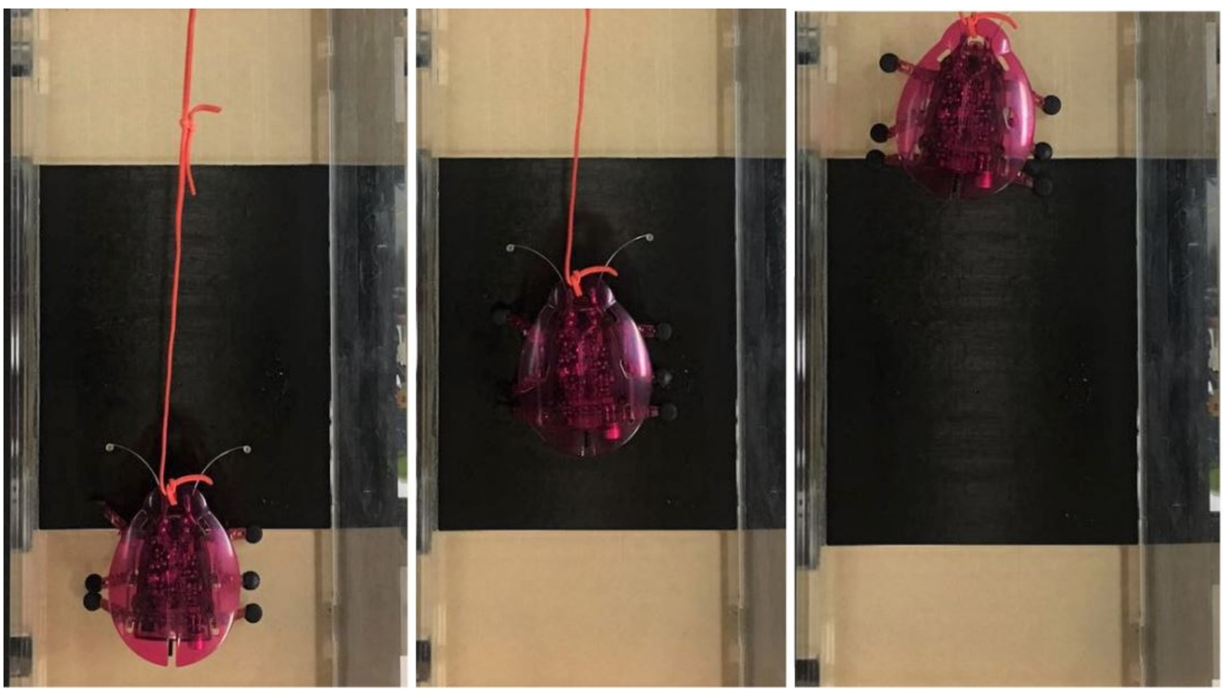


Figure 4.13: Hexbug running through the force plate surface

Data acquisition Primary signals from all four force channels were stabilized and amplified by INA125. Then the signals were collected by a NI DAQ (National Instruments, Austin, TX, USA) on the computer, and the data was sampled at a frequency of 1 000 Hz.

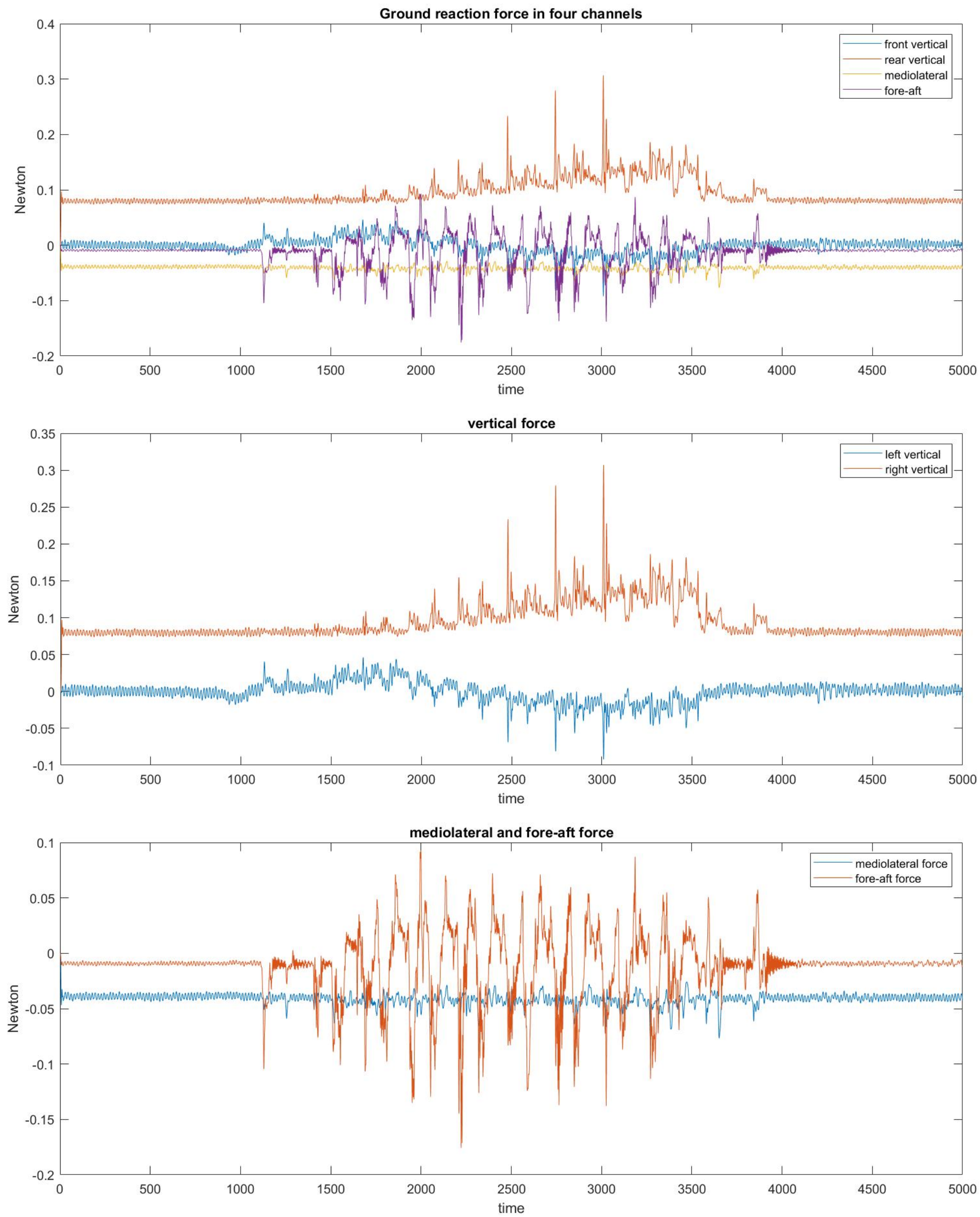


Figure 4.14: Ground reaction force of hexbug climbing through horizontal trackway

To remove the oscillation frequency of the force platform, the force data was filtered by a fifth order butterworth filter at 180Hz.

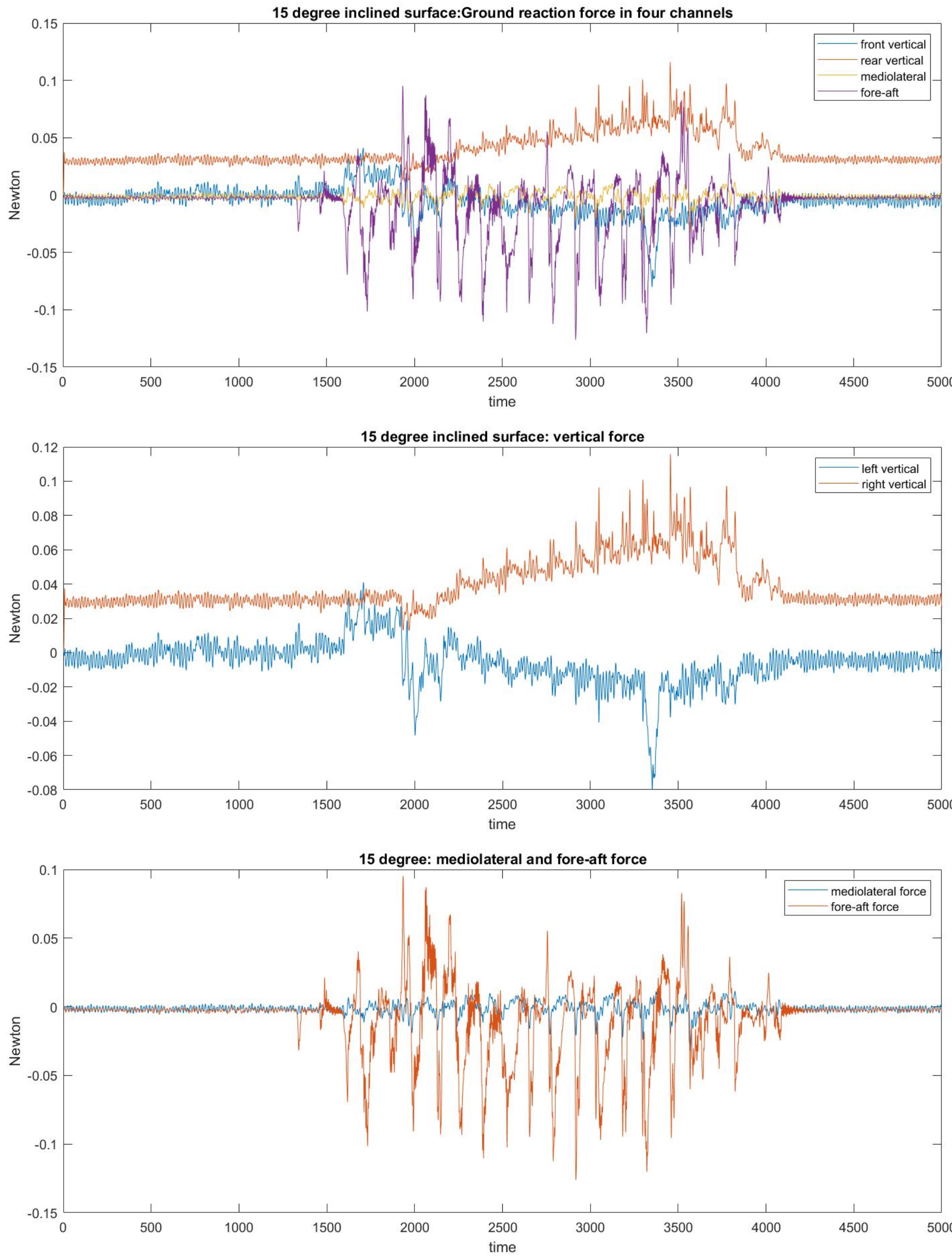


Figure 4.15: Ground reaction force of hexbug climbing on 15° inclined trackway

Data analysis The following plots are the data collected when hexbug climbed through the surface on the 0° trackway.

From Figure 4.14, we can see that the hexbug toy does have a specific gait. The average frequency of the vertical force channel is 7.87 Hz and the average frequency of the fore-aft force is 7.46 Hz. There is mass vibration on the vertical and fore-aft force channel, while not so much oscillation on the mediolateral force channel. Hexbug mainly relies on swinging the leg front and rear to move forward but not on the mediolateral force like real cockroaches.

From Figure 4.15, we can see that the stride frequency of the hexbug stays the same and there is still not much oscillation on the mediolateral force channel, but the forces in backward direction are larger than climbing on 0° trackway because of the self weight.

4.4 Hexbug Modification

As the hexbug does not change the speed or frequency when the inclined angle of surface changes, some modificaitons need to be done. Hexbug is basically controlled by a DC motor that is controlled by a circuit board, so the speed of the hexbug can be changed by changing the rotating speed of the DC motor.

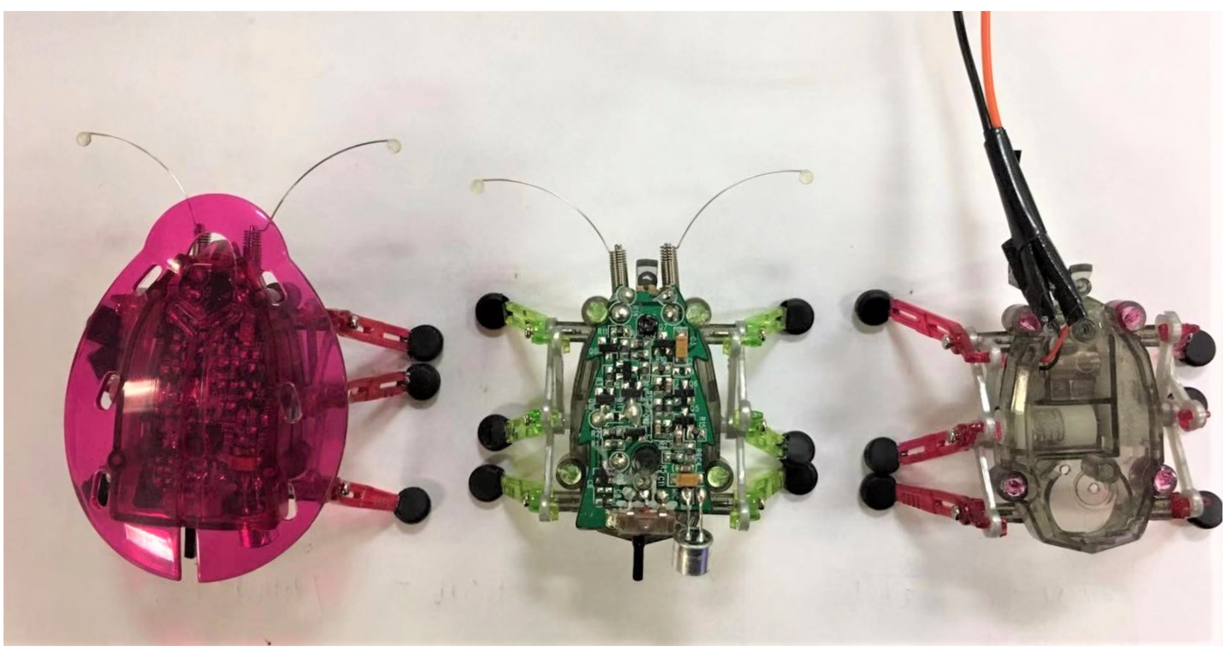


Figure 4.16: The modification of the hexbug

An Arduino microcontroller can be used to control the DC motor. By using a diode, a transistor and a resistor, a circuit shield can be built for the Arduino control since the DC motor cannot be directly driven by Arduino. By tunning the duty factor of the input voltage, the rotating speed of the DC motor can be changed so that the speed of the hexbug can be changed.

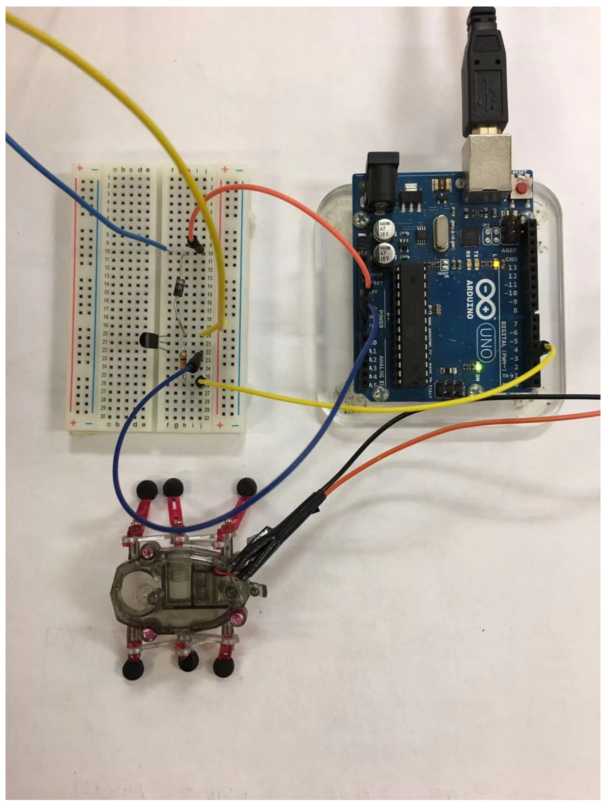


Figure 4.17: The Arduino control circuit

To test the force platform, let the hexbug run through the running trackway driven by different voltage supply with the range of 0.68 V to 5 V. The following plots show the ground reaction force of the four channels at different voltage supply.

Figure 4.18 shows that the stride frequency of the hexbug increases rapidly at the begining as input voltage increases, but it is not obvious at the second half when the input voltage reaches a certain value. To better understand the stride frequency, the Fast Fourier Transform has been taken to the fore-aft force signal.

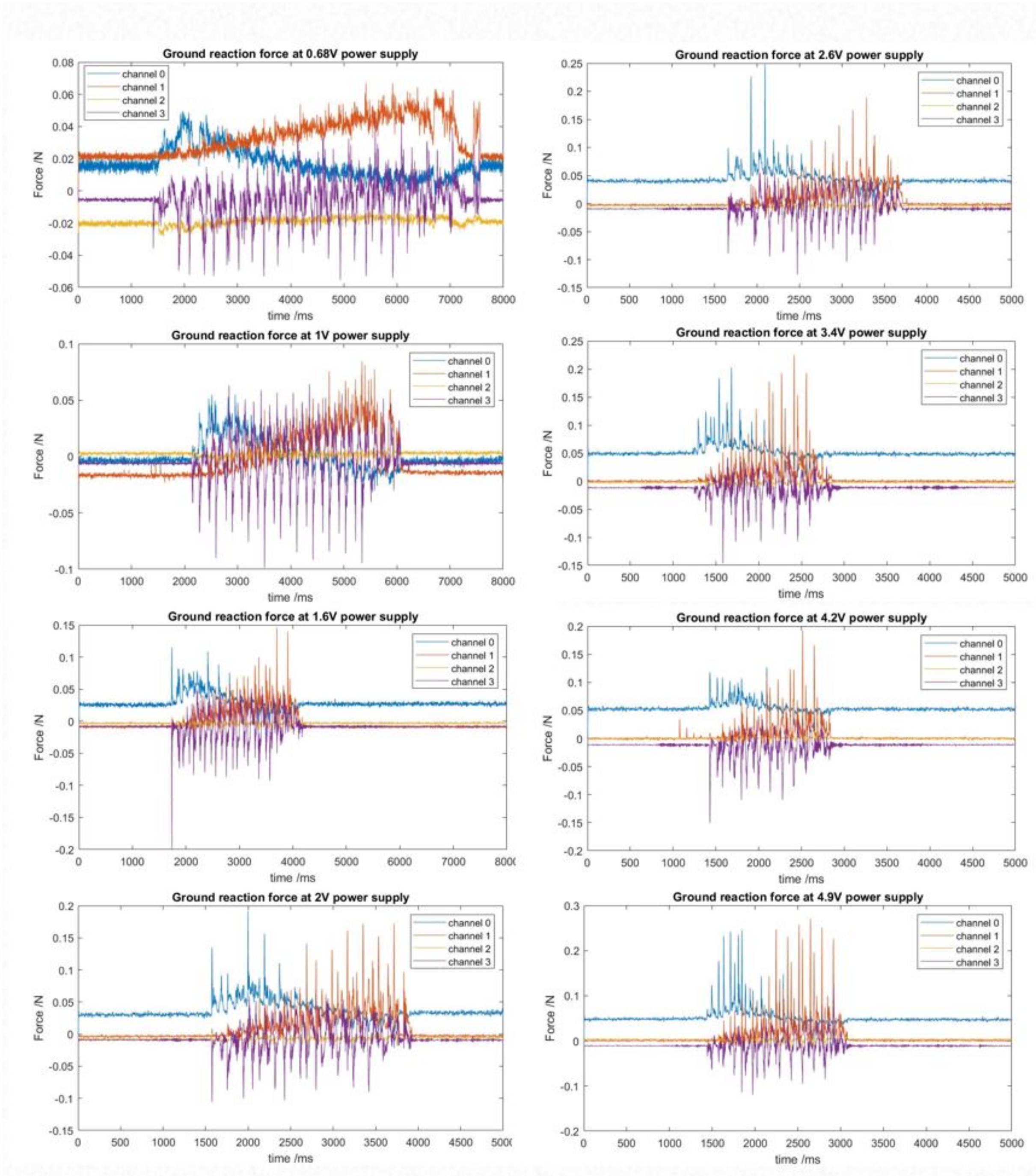


Figure 4.18: The ground reaction forces of four channels

Figure 4.20 shows that stride frequeny of hexbug increases as the input voltage increases until a certain value and then the stride frequency starts drfting around a constant.

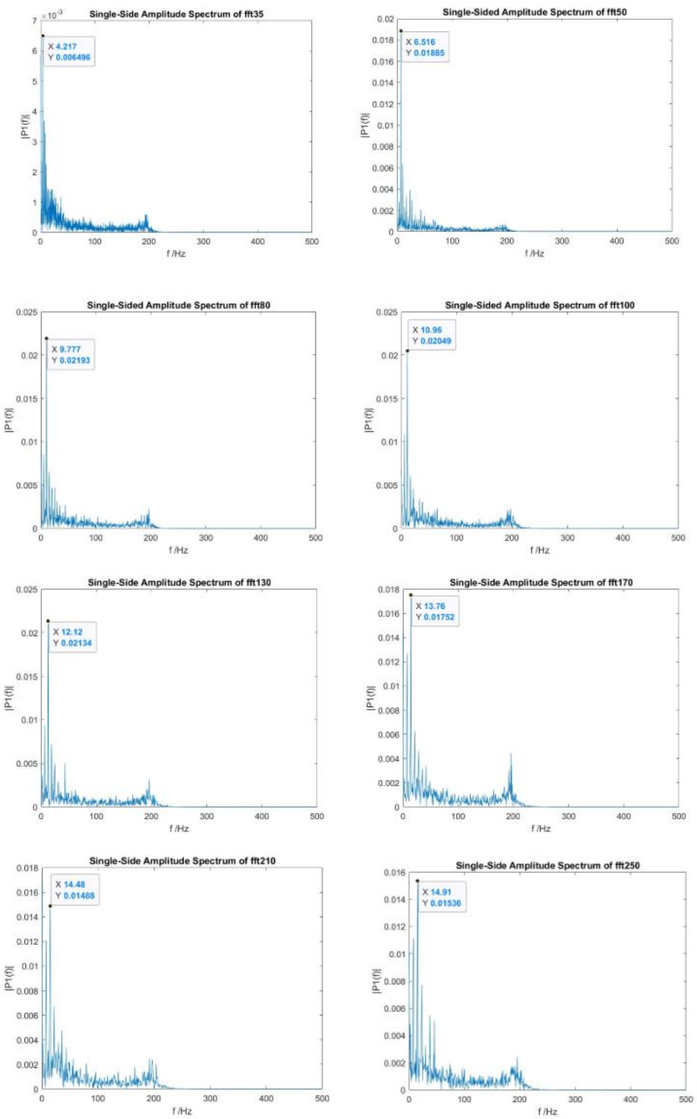


Figure 4.19: FFT of the fore-aft force signal

The average speed of hexbug also increases to a certain value and stops increasing although the input voltage is still increasing. The average speed is proportional to the stride frequency.

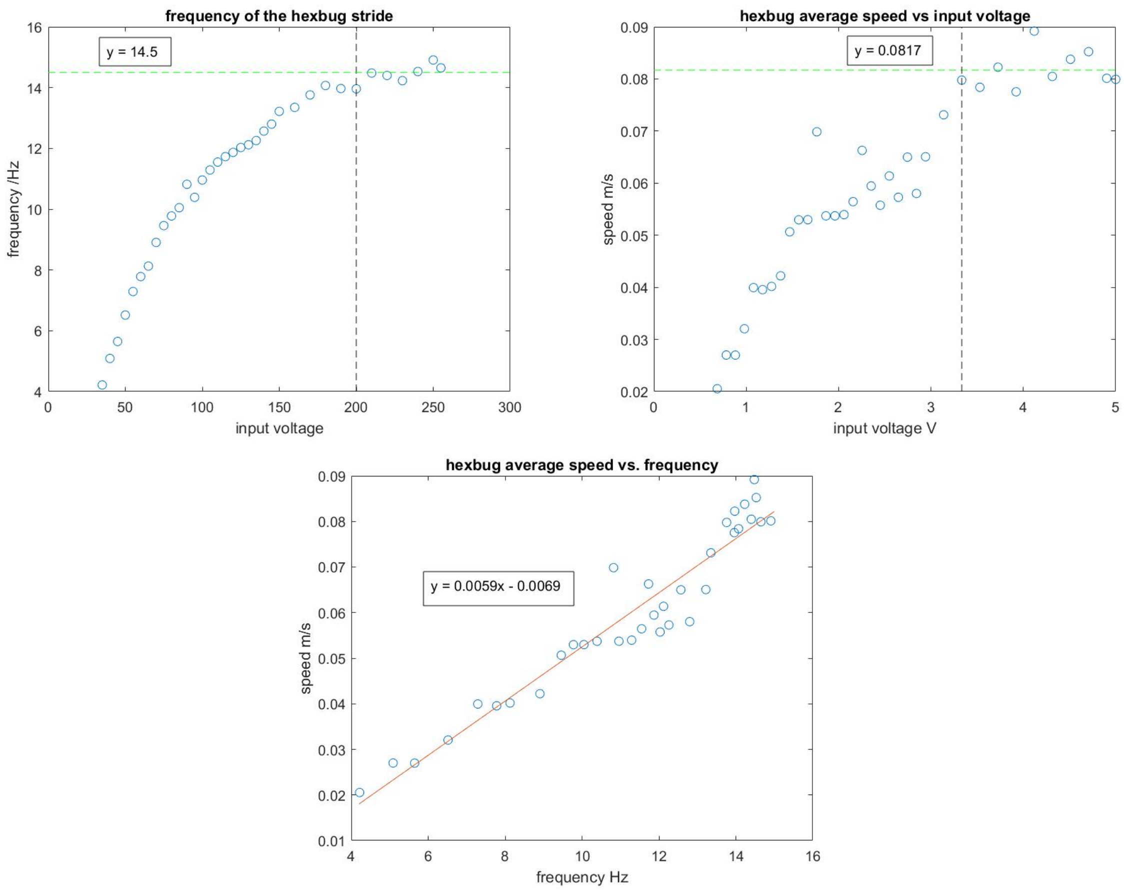


Figure 4.20: The relation between speed and stride frequency

Chapter 5

Conclusion and future work

5.1 Conclusion

A hand-made three dimensional force platform has been designed and fabricated. The result of calibration suggests that the typical sensitivities of the normal forces are 2.11 V/N for front vertical force and 3.4146 V/N for rear vertical force. The mediolateral force sensitivity is 4.4186 V/N and the front-aft force sensitivity is 5.7572 V/N. The force platform has an average natural frequency of 200 Hz so it can record all the primary signals faithfully and it can also remove the influence of the force plate oscillation as we can filter the oscillation at 180 Hz. The design and fabrication for a compatible apparatus to study cockroach incline climbing has also been made in this paper. The final test of hexbug climbing shows that the force platform satisfies the design requirements and is also easy and convenient to use for studying other large insects and small animals.

5.2 Improvements and future work

There are still rooms to improve the design and fabrication. As what we have discussed in the calibration procedure, the normal force channels can be calibrated to be uniform, which means the uniformity of the front and rear vertical force channel by tuning the gain of amplifier so that we can tell the animal's position by reading the normal force output. It can also simplify the transfer matrix so that only three channels need to be taken into consideration.

Another thing is that ground reaction forces of a specific limb are important to the study of animal's gait. The one that has been designed in this paper can study the forelimb and rear limb by studying the force at the moment when the testing animals enter or leave the force plate. However based on the platform of Full and Tu version, the middle single leg force cannot be recorded. According to Goldman, the force plate can be developed to use half of it so that the middle leg force can be studied.

Moreover, the typical sensitivities of the force plate can still be improved by modifying the dimensions of the force plate frame, spring blade slot and the material and fabrication of the force plate surface. The natural frequency of the force plate should also be improved as now we are using a cutting frequency of 180 Hz and it might fail to capture the higher frequency of dynamic running for insects like *Blaberus cockroach.*

The future scope of this project will mainly focus on the experiments that can be done on this platform. To study the cockroach climbing kinematics, the whole setup should be improved with high speed camera and appropriate substrate for cockroaches to climb. An auto-balance microcontroller should also be integrated in the circuits so that bridges do not need to be balanced every time the inclined angle changes.

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