Inexpensive Custom Built 6-Axis Force/Torque Sensor for Suturing Simulator

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INEXPENSIVE CUSTOM BUILT 6-AXIS FORCE/TORQUE SENSOR FOR
SUTURING SIMULATOR

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Electrical Engineering

by
James Ryan Bittner
August 2019

Accepted by:
Dr. Richard Groff, Committee Chair
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Dr. Ian Walker
Abstract

This paper details the design of a six degree-of-freedom low-cost force/torque sensing platform for use in a suturing simulator for surgical training. This platform is based on the Stewart Platform configuration in which the linear actuators are replaced with metal wire kept in tension by multiple elastically loaded support columns. Flexible wire legs are used in lieu of rigid connectors so as to reduce the platform’s susceptibility to inter-component friction in measurements and to allow the platform to exhibit built-in stress relief for the cantilevers in directions of concern. The static structural elements of the platform are designed to be manufactured from standard 3D printing technology, decreasing the overall weight of the platform while keeping costs low and allowing for quick replacement of any damaged structural elements. Due to errors in fabricating the cantilevers, a slow transient response is observed in the platform’s voltage outputs which is carried over into the measured loads on the platform. By experimenting with different cantilever designs and the techniques used to manufacture them, new cantilever designs are proposed which correct for the slow transient response. The platform is calibrated by applying standardized weights to cause forces and torques in each axes and sampling the corresponding voltage outputs. When the platform is subjected to unknown loads after calibration, the platform measures forces and torques in each axes for short periods of time with errors attributable to the non-linear response. Tests simulating the suturing system are conducted on the platform with the results showing that the platform is able to measure forces and torques in each axes at any position on the membrane. While the current sensor can not be used in the suturing system as is, implementing the new cantilever design in the platform will make the platform an inexpensive component capable of providing accurate measurements of the loads on the membrane.
Dedication

I dedicate this thesis to my Mom and Dad who have supported me throughout my academic pursuits. Their encouragement and faith is why I’m here and always pushing to improve myself. I also dedicate this thesis to my brother and sister, even if the latter does go to Alabama, as my harshest critics and greatest gifts I’ve received from the Lord to date. Through competing, aiding, and commiserating with them, I’ve grown into the individual I am today and continue to grow better through these interactions.
Acknowledgments

I’d like to thank Dr. Groff for is input and advice both on this thesis and on pursuing what comes after along with taking me on to this project late into my stay at Clemson. Without his guidance, I might well have left Clemson either with no degree or as a non-thesis graduate. I’d like to thank Dr. Singapogu for allowing me access to his lab’s equipment and his patience with my learning process around both the equipment and the materials present. I’d also like to thank Dr. Walker for initially pointing me to Dr. Groff after losing my first thesis and for allowing me to also abscond with his lab’s materials for what may be considered a bit too long of time. I also want to thank David Moline for his input on the design of the platform and aid in manufacturing the non-printable elements throughout the various designs the thesis has undergone. His help with the mechanical aspects of the project amongst everything else is why this thesis came as far along as it did. I also thank my lab team: Jianxin Gao, Irfan Kil, and Marshall Trout in helping me through this process even if it just came down to having someone listen to me rant. I also wish to thank Irfan farther for his willingness to help me debug aspects of the project along with his patience when I inevitably messed up the first test requiring a redo from the top.
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Chapter 1

Introduction

The current methods of training surgeons in good suturing techniques primarily involve two methods. One of these methods are “boot-camps” where the participant mails examples of their stitch work to evaluators, thus forgoing real-time feedback throughout the process. The other method involves oversight by an instructor during the procedure which, while giving a more detailed and immediate critique of the trainee’s skill, does require at least one qualified surgeon’s undivided attention.

Thus, there is a desire among members of the medical community to develop a more practical training regime in which the trainee has more freedom to hone their suturing capabilities with adequate feedback to aid in the learning process while lessening the burden on active surgeons to supervise. To this end, a suture training simulator is in development which seeks to automate the process giving the surgeon-in-training real-time feedback on their attempts without the need for a knowledgeable practitioner to be immediately present.

To accomplish this, the simulator keeps track of a variety of metrics which have been shown to exemplify experience, and thus skill, of a surgeon. A couple of these metrics are derived in part from the force by which the surgeon both punctures and drives through the tissue to complete a stitch. Due to this, the suturing simulator must be able to measure external forces applied by the needle to the stitching membrane.

The current version of the simulator incorporates an ATI Mini 40 6 axis force - torque sensor at the bottom of the system. The ATI Mini 40 6 axis force - torque sensor is able to measure both forces and torques along all three axes.
However, the ATI Mini 40 6 axis force-torque sensor is also expensive with the transducer valued many times more than the simulators constituent components combined. At present, this leads to a hesitation to deploy the simulator in more active locales, such as medical conferences, where the amount and quality of data is invaluable to refining and proving the merits of the system as damaging the sensor either in transport or random uncontrolled occurrences will be costly and not easily remedied. Also, as the end goal of this project is to develop a personal suture training platform which trainees may have unlimited access in order to hone their skills, the cost of the ATI Mini 40 6 axis force-torque sensor inhibits the mass production and distribution of the platform in a price range feasible to most institutions let alone students.

The purpose of this paper is to describe the design, manufacture, and testing of a low-cost force-torque sensor capable of replacing the ATI Mini 40 6 axis force-torque sensor in the suturing simulator.
1.1 Background

The suturing system shown in Fig. 1.1 is the culmination of currently ongoing research documented in [14], [17], [15], [16], [18], and [19]. The cylindrical structure at the top of the system is the primary testing area by which the user interacts with the device when stitching. The stitching membrane, observed at the top of the cylindrical structure as a horizontal white plane, is held taut by a membrane holder designed to be fixed to the rest of the structure by latches located around the top of the cylinder. During testing, the participant is limited to interacting with the system exclusively through stitching on the membrane with any stimuli exerted to other parts of the system deemed undesirable. The cylinder is hollow on the inside and kept clear of obstructions so that a camera located at the bottom of the cylinder has clear view of the membranes underside. This allows for collecting various position based metrics such as points of entry and the area covered by the needle while unobserved by the user. An outer cylinder is observed surrounding the inner cylinder holding the membrane which can be raised and lowered on command to simulate surface level stitching conditions and internal stitching conditions. The entire system rests on an adjustable table controlled by a stepper motor.

The ATI Mini 40 6 axis force - torque sensor can be seen in the Internal View in Fig. 1.1 which places the sensor at the bottom of the cylinder.

In order to replace the ATI Mini 40 6 axis force - torque sensor with an acceptable alternative, certain aspects of the design must be maintained so that data for all relevant force and torque metrics may be obtained without interfering with sensors collecting data for other metrics.

Summarized beneath, the qualities of this sensor should include:

1. Detects application of all three force components on the stitching membrane
2. Located near or around the stitching membrane
3. Does not obstruct the view of the camera located underneath the membrane
4. Does not obstruct the top of the membrane from the user
5. Built in protection against overloading
6. Inexpensive and easy to build and repair
Beginning with aspects specifically required for the new sensor to perform its role as an acceptable substitute for the ATI Mini 40 6 axis force - torque sensor, the proposed transducer must have the ability to measure all forces along three axes. This means that it must detect the normal force and both shear forces applied to the membrane and account for the direction in which these forces are applied. Two of the metrics in particular require the shear forces to be transformed into a new coordinate plane and as such rely heavily on not only the magnitude of the force but also the direction in order to be accurately transitioned. Furthermore, the transducer must also demonstrate the ability to detect these forces within the range observed to be present in both experienced surgeons and inexperienced rookies. From previous testing with the simulator, the sensor would be sufficient if accurate to 0.1N and expected to be linear up to a maximum of around 10 N.

Also, the replacement must be able to account for any torque applied to the membrane around all three axes. While, these torques are not necessarily used in the metrics, with only torsion in the normal direction appearing to contribute a significant factor, a means of keeping responses purely caused by forces separate from those purely caused by torques was deemed useful if only to not lose any functionality when switched from the ATI Mini 40 6 axis force - torque sensor and to have the data available should future testing show the necessity.

Continuing with desired aspects which would make the sensor a better fit, the replacement should be placed as close as possible to the membrane. Currently, the ATI Mini 40 6 axis force - torque sensor is placed underneath all the other constituent components that make up the simulator by necessity. In this position, the transducer detects external forces not only applied to the membrane but to any part of the structure. Taking measurements closer to the membrane would eliminate the need to separate non-relevant stimuli from the measurements and will give faster more accurate responses.

Placing the replacement closer to the membrane however causes difficulties with other sub-systems. For instance, certain metrics require that the camera be given an unobstructed view of the membrane’s underside in order to determine the position of the needle and requires a non-trivial distance between the membrane and the lens in order to do so. This is one of the reasons why the ATI Mini 40 6 axis force - torque sensor is placed in the disadvantageous position at the bottom of the structure in the first place. Thus the replacement must be modified to work around the camera so that the line of sight is not obstructed.

Furthermore, the replacement may not obstruct or otherwise impede the user while suturing.
A major issue for transducers is protection against overload conditions. Accidents do happen, and in the case of force sensors, particularly those using strain gauges as the active sensing element, the sensor could be irreparably damaged by applying too much force and breaking the gauges. This is one of the reasons why the current version is treated with such care as the ATI Mini 40 6 axis force-torque sensor is equipped with minimal protection from overload conditions. Thus, the new replacement must also be robust and resistant to overload conditions. Applying a safety factor of 3 to the device in terms of the maximum force expected to be applied on the membrane, this entails the sensor be able to endure 30N of force. Furthermore, assumptions can be made based on the nature of the system as to what direction an overload force would be likely to appear from. In this case, a downward normal force caused by either dropping an object or a careless user is the most likely means by which a large unexpected external force would be introduced so particular care should be taken to protect the sensor in this direction.

Finally, in order to be a successful replacement for the ATI Mini 40 6 axis force-torque sensor, the sensor must solve the issues that ultimately made the ATI Mini 40 6 axis force-torque sensor a poor fit for the system. That is, the replacement must be inexpensive and easy to mass produce. In the short term, a sensor that is easily replaced quickly without too much expense would allow the system to travel with less risk. As such, the system could be brought to new populations of surgeons with varying levels of expertise much more readily helping to accelerate the pace of development. In the long term, taking into account Murphy’s Law, especially when under the menstruation of inexperienced users, having a sensor which is easily repaired or rebuilt with over-the-counter parts would be a nice incentive to prospective customers when the system is in distribution.

### 1.2 Related Works

The two primary aspects researchers appear to focus on when building force-torque transducers are the active sensory elements and the structure on which these elements are mounted. From the former aspect, researchers have utilized a multitude of means to both directly and indirectly measure the response of a structure to external forces. These include measuring changes in the transducer through vibrations, pressures, light intensities, capacitance, piezoelectric responses, and strains. From the latter aspect, the structure of the transducer is dependent on the chosen active
sensory element from the former aspect as the structure is designed to augment and enhance the response of the sensory component mounted on it. The following works provide examples of different approaches to each of these aspects with the groupings based primarily on the choice of active sensory components.

For instance, [1] and [2] detail progress on a six-axis force sensor utilizing vibrations through the transducer as the measured conveyor of force. The idea behind this approach is to create a structure in which externally applied forces create large variations in the inherent resonance frequency of the structure. To accomplish this, [1] and [2] create a plate instrumented with piezoelectric actuators to induce vibrations and piezoelectric sensors to detect these vibrations through the plate. As an external force is applied, the resonance frequency of the plate will change in what is approximated as a linear relationship in all three axes. The ideas introduced in [1] and implemented in [2] show the sensor is able to estimate all three forces though further work is stated to be necessary in solving for non-linearity along the normal axis.

Another interesting design of note comes from [8] where a microelectromechanical system (MEMS) barometer is used as the active sensing element. This approach joins two rigid plates with four rubber blocks containing an embedded MEMS barometer. Efforts are made to remove any air pockets allowing the rubber to directly interface with the sensing diaphragm. This method creates a 6 DOF force - torque transducer comprised of low cost components which is protected from overload damage. The major issue of note is a perceived decrease in the sensing range of both shear forces when compared to the normal force and the torques.

Continuing on with works derived from pressure sensitive components, [11] describes an air-lubricated six-axis force sensor comprised of a plate suspended in mid-air by air nozzles. In this case, an external force applied on the plate will affect a change of pressure between the plate and nozzle. This change is recorded by barometers and used to approximate the applied force with the relationship between these two factors assumed to be linear. The researchers mainly focus on solving a specific problem inherent to the design, unconstrained oscillations, but mentions that the air-lubricated approach solves the coupling problem inherent of solid joints.

In the pursuit to develop a magnetic resonance (MR) compatible sensor for use in medical operations, a large body of work has been generated utilizing fiber optic cables as the conveyor of applied forces. The reasoning behind this approach is that fiber optics do not effect or are affected by magnetic fields which are used in certain medical operations such as in MRIs. From the work seen in
the basis of the design consists of utilizing two fiber optic cables placed at an angle in front of a mirrored surface. One optical cable, the emitter, transmits a beam of light which is bounced off the mirror into the second optical cable, the receptor, which transmits this reflection to a light intensity measuring apparatus which converts this value into a voltage. The idea is that the application of an external force on the structure will produce deformations in the structure changing the distance between the mirror and fibers which will in turn cause a change in the intensity of light carried away by the receptor. This method allows for any active electrical components to be mounted a distance away from the operational region of the device thus allowing it to be a neutral presence to electromagnetic radiation. In [3], the authors are concerned only with proving the validity of the idea with successful results. The progress seen in [31], [40], [30], and [32] exemplifies an implementation of this idea in a flexible continuum manipulator for Minimally Invasive Surgery (MIS). The work utilizes three pairs of these fiber optic sensors embedded into the structure of the segment connectors which together are able to estimate forces in all axes applied to that segment of the manipulator. With this method, [32] stated that while not able to measure the maximum operational force of 21N, the device’s dimensions can be easily calibrated to work in a particular range.

A capacitive-based solution is shown in [22], [21], and [20], where a multi-layer construct is built with one such layer instrumented with six capacitance sensor cells. Above this layer, a grounded disc is attached to an overall elastic structure, leaving a pocket of air between the two, such that any external force applied to this structure will deform the structure. This deformation will result in changing the distance between the capacitance sensors and the grounding disc with the outputs of all six sensors being sufficient to estimate the forces and torques in all axes which produced the deformation. The methods of manufacturing the device are detailed and result in a low-cost sensor suitable for mass-production.

Another concept relying on deforming internal layers of the transducer are seen in [23], where multiple layers of quartz wafers are utilized instead of a layer of capacitance sensors with deformations resulting in voltages from the piezoelectric layers.

Considering the nature of the suturing simulator which will incorporate the new force sensor, [29] is particularly noteworthy being a similarly aligned project. In this case, photo interrupter sensors are placed around and underneath a urethane foam located under the suturing membrane where deformations in the foam would be detected by the sensors and converted into force estimates.

Looking at [9] and the progress of work seen in [35] and [36], attempts are shown that
focus more on utilizing components which are easily procured rather than with developing unique
implementations. The work shown in [9] for instance seeks to re-purpose a 6D mouse as the sole
active sensing component for a laproscopic training platform. Meanwhile, the research seen in [35]
and [36] shows progress in developing a 6-axis force sensor comprised of single-axis force sensors
arranged in a modular configuration. In either case, a 6 DOF force sensor is created with acceptable
working parameters.

An example of using encoders and torque springs to measure the displacement of a plate
under an external load is shown in [37] where the structure is comprised of six rods suspending
the plate. These six rods connect to the active sensing elements below the plate and together are
sufficient to estimate the load applied to cause this displacement.

Most force transducers, however, use strain gauges to measure the strain exhibited by the
structure under an externally applied force. In this method, a structure is designed so that strain
measurements may be resolved into the applied forces.

For instance, in [25] and [24] a five-axis finger force transducer (torsion along the normal
axis is not measured) is described. The transducer incorporates an instrumented diaphragm into the
system specifically designed for magnifying the stress exhibited in particular areas of the structure
caused by external forces. The pros and cons of different diaphragm designs and how different
dimensions affect the performance of the sensor are further presented in [24].

A hollow ring-shaped three-axis force transducer is discussed in [5] as a means of obtaining
force measurements from ink pens while writing. The outer ring is attached to the outer pen while
the inner ring grips onto to the ink cartridge. The entire structure was designed with the idea of
mass production in mind, such as mounting all strain gauges along the same plane.

The design of a force plate utilized to measure the force applied by swimmers on the starting
block during kick-off is described in [26]. The design consists of two plates attached by a large
instrumented cylinder with four strain gauges placed equidistant around the outside. The results
were described as usable but imprecise for the scenario.

The work done in [39] details a force transducer designed to be built entirely from a 3D
printer with only instrumentation by strain gauges required as an extra step. The transducer consists
of two rings: an outer ring, expected to be secured to a stable structure, and an inner ring, which is
expected to bear the load. These rings are then connected by instrumented legs strategically placed
to aid in resolving the strains observed on the legs into forces. To simplify the structure, the legs
are permanently fused to each ring and utilize flexure joints to allow for compliance and minimize coupling.

1.2.1 Stewart Platform

The literature appears to favor one design methodology in particular which is to utilize structures based-off the Stewart Platform.

A Stewart Platform is a parallel manipulator that allows for six degrees of freedom with a design similar to that seen in Fig. 1.2. The manipulator is controlled through six linear actuators connected by universal joints at each end. The actuators are arranged such that the universal joints are grouped in pairs so that a linear actuator’s line of action will intersect both of the adjacent neighbor’s lines of action as seen in Fig. 1.2. This allows the manipulator to change the length of one actuator at a time while not affecting the lengths of the others making each “leg” linearly independent of the others. This also allows the actuators to induce translations in all three axes as well as rotations around all three axes when utilized together.

The assumption made for converting this manipulator’s design into the role of a force - torque transducer is that if the linear actuators are replaced by rigid links, the strain measured on these links can be resolved into the the forces and torques enacted on the structures top plate. The reasoning behind this assumption is based on two factors. First of all, the legs are still linearly independent if the configuration is kept meaning that a stress placed on one leg doesn’t necessarily have to produce a stress on any other leg. Secondly, since the Stewart Platform as a manipulator can be manipulated
by translation or rotation in all three axes, stress can be induced by subjecting the transducer to any of these deformations which will induce unique stain measurements in the individual legs. As this would make the transformation converting forces and torques to strain measurements both full-rank and one-to-one, the transformation matrix is invertible signifying either measurement can be converted into the other with no dimensional reductions. Thus the same matrix used to convert the linear distance of the actuators to the resulting translations and rotations of the manipulator may be used to convert the forces and torques applied to the transducer into the strains exhibited by each leg and vice versa.

The earliest applications of the Stewart platform in this manner is seen in [34] and finds that the design results in a sensor with acceptable accuracy and high sensitivity to small variations in the applied external forces. Each leg is instrumented with a single-axis force transducer with the geometry of the platform being entirely responsible for decoupling the readings observed on each leg. A recurring issue with hysteresis and non-linearity is stated to be an issue with the design that is primarily caused by friction observed at the joints between legs and plates.

A different approach to this design is seen in [13] by utilizing linear voltage differential transformers (LVDT) mounted on the legs as the active sensing component. A linear estimate of a closed-form model for the forward kinematics is also derived which shows the ability to estimate applied forces within margins of error existing below the noise threshold. They also propose an algorithm to account for the affects of gravity on the legs of the system and demonstrates the results of the algorithms implementation.

The legs of the platform are often kept at angles in keeping with the original Stewart Platform’s configuration but work done by [33] and [41] shows the effects of modification to this aspect by placing the legs in a near-singular configuration. A Stewart Platform constructed in a near-singular configuration incorporates legs which are set vertically between the two plates rather than at a slant or angle. This is done in [33] to test the theory that Stewart Platforms placed in near-singular configurations bias sensitivity in certain directions. An unmodified Stewart Platform is built to be stiff in all axes but a Stewart Platform built in a near-singular configuration loses stiffness in certain directions. Following this observation, [33] displayed that this geometry creates a mechanical magnification effect where the platform is made to exhibit higher variability in strain for smaller applications of forces and torques in certain directions. Attempts to optimize this feature are found in [41] which details the math behind this characteristic. Further work in [33] also presents
the use of bi-axial flexure joints as a better alternative to mechanical bearing joints for solving the non-linearity issues created by the presence of friction within these joints. Flexure joints are not so much mechanical hinges as they are compliant areas built into the structure which reduce the number of disparate pieces interacting with each other. This in turn decreases the number of connections contributing to frictional loss in the structure.

Other attempts to overcome the problems inherent in imperfect mechanical joints are observed in [7] in which a Stewart Platform is designed to be supported by ‘joint-less’ legs. This is done by avoiding the use of constraining mechanical joints and allowing the rounded tip of the leg to rest in a rounded ditch built into the top and bottom plates. To keep the structure ‘tightened’ down, a pre-loading force is required in the design which is handled by supporting the weight of the top plate. While this limits the range of forces that can be exerted on the system to those that can be counteracted by the pre-loading force supplied by the top plates weight, the lack of mechanical joints allows for high precision and leaves the system unconstrained by size requirements. Furthermore, previous work shown in [6] and carried over into [7] utilizes a modification to the legs by including a ring-shaped structure. The purpose of this addition is to add a mechanically advantageous position into the leg for measuring strain. As the ring is more compliant than the rest of the leg, a higher sensitivity to strain is measured in this region as well as improving other issues such as hysteresis. This is allowed as the Stewart Platform’s performance is based entirely off the geometry of the device as a whole with the structure of the legs being trivial in comparison allowing for modifications of the leg to be implemented for the benefit of the active sensory element.

Another deviation form the original design of the Stewart Platform utilizing spherical joints include work done by [12] in which a load sharing beam (LSB) is incorporated to fix the top and bottom plates together. While this decreases the sensitivity severely, the purpose of the research is to create a heavy force sensor which is expected to endure large and constant stimulation without buckling and maintaining accurate readings.

This central pillar concept is seen for a different purpose in [10] and [38] with the spherical joints kept together by introducing a central beam to hold the top and bottom plates together in order to pre-stress the structure. Both [10] and [38] also modify the structure to exhibit a hype-static, also known as statically indeterminate, geometry. While a normal Stewart Platform is configured with the line-of-action of the legs intersecting at the top and bottom plates, a statically indeterminate platform incorporates legs that do not intersect at the plates of the platform. While [10] focuses
on the optimization of parameters in a hyper-static system, [38] builds a system based on this principle for greater dynamic stiffness which displays an acceptable result, with the incorporation of the pre-stressing beam contributing to a reduction in hysteresis.

A specific implementation of the Stewart configuration can be seen in [27] with following work displayed in [28] where a modified design is developed to measure the flexible exhaust coupling in automotive systems. For this purposes, the top and bottom plates are joined together by six wire extensometers instead of mechanically rigid legs. As the platform required the object be situated between the plates to function properly, a side of the platform is left open and free of the wires resulting in only five intersecting lines-of-action. The resulting experiment displayed that the angle of the contained geometry, whether the object to be measured possessed acute or obtuse angles, affected the sensitivity in certain directions.

Another use of non-rigid legs in the structure is seen in [4] where non-elastic wires are used to connect the top plate to instrumented v-shaped cantilevers fixed to the bottom plate. The structure also incorporates a central pillar consisting of a spring attached to the top and bottom plates by ball-and-socket joints in order to keep the wires in tension. The purposes of this design is to develop a tactile sensor to verify theories regarding forces exhibited in robotic grasping operations and thus is optimized for contact force measurements.

1.3 Design

A design for a force - torque sensor is constructed from a portion of the works described in Sec. 1.2 with [4] being the most notable contributor. While [4] focused on developing a tactile sensor for contact forces, the ideas presented are re-purposed into a six-axis force/torque sensor which meets the criterion presented in Sec. 1.1. This design is modeled closely off the original Stewart Platform configuration with the linear actuators replaced by metal wire. This wire is connected to the top plate of the platform by a rigid apparatus while connected at the other end to a strain gauge instrumented cantilever. This cantilever is then fixed to the bottom plate of the platform which acts as the static entity in the design. As the wire can only transmit forces while in tension and can not support the weight of the top plate, three pillars are used to support the weight of the top plate and keep the wires in tension. Each pillar is comprised of a 3D printed inactive static column connected to the bottom plate and a metallic spring connecting this column to the top plate. Other than the
cantilevers, springs, wires, and the rigid apparatus on the top plate, all structural components are constructed in a 3D printer. An example of this platform may be seen in Fig. 1.3.

As stated previously in Sec. 1.1, the criteria for the sensor is as follows:

1. Detects application of all three force components on the stitching membrane
2. Located near or around the stitching membrane
3. Does not obstruct the view of the camera located underneath the membrane
4. Does not obstruct the top of the membrane from the user
5. Built in protection against overloading
6. Inexpensive and easy to build and repair

The design proposed meets all these criteria in the following ways.

First, [4] already shows that the design can accurately estimate forces and torques in all three axes with the notion of an upward normal force being reasonably assumed to be similarly accurate though not expressly tested in their approach.

In order to meet both Criterion 2 and Criterion 3, modifications can be made by replacing the central strut in [4] with multiple smaller struts located around the outer rim, in a configuration
reminiscent of the structure built around the 6D mouse in [9]. This fulfills the role of the central strut in keeping the wired legs under tension and frees the center of the platform of any necessary equipment. By clearing the center of the platform, the stitching membrane can be mounted directly onto a ring-shaped top plate. The camera of the suturing simulator may be mounted to the center of the bottom plate or below a ring-shaped bottom plate. In either configuration, the membrane will be in direct contact with the platform without obscuring the view of the camera. This would effectively make the platform the container for the active sensing structure of the simulator thus reducing the size to what is minimally allowed by the lens of the camera.

The nature of the structure meets the overload protection requirement of Criterion 4. The most likely direction of force overload is the downward normal force. If the platform is subjected to an overloading force in this direction, the wires connecting the top plate of the platform to the cantilever will go slack placing all the load on the three pillars. As the pillars themselves are easily manufactured with inexpensive parts, any damage resulting from this action is deemed acceptable when compared to the more expensive and extensive process of manufacturing the cantilevers.

The nature of the device means that Criterion 5 is relatively simple to meet as the material to create the platform are easily ordered with the larger portions of the structure easily fabricated.

The rest of this thesis is organized as follows. Chapter 2 presents the design and fabrication of the platform with each component described in detail and grouped by subject. Chapter 3 discusses aspects of the cantilever’s signals not covered in Chapter 2 including the presence of a slow transient response to loads directly applied to the cantilevers. Chapter 4 details the process of calibrating the platform and the response of the platform to known loads. Chapter 5 discusses the platform’s response to unknown loads and performance during a simulation of the suturing system. Chapter 6 presents a statement of the designs outcome along with suggestions of possible improvements and areas in need of further research.
Chapter 2

Platform Design

This chapter covers the design and manufacturing of the platform. Sec. 2.1 details the purpose, design, and methods of fabricating the platform's structural elements. Sec. 2.2 details how the platform's electrical components are used to filter and amplify the platform's outputs before being processed by the data acquisition system. Sec. 2.3 presents the software used to interface between the platform and the computer.

While [4] is the primary inspiration behind this design, the work concerns itself primarily with providing a mathematical justification behind the geometry and detailing the results of experiments conducted on the construct neglecting to provide a detailed account of the components procured and implemented in the design. As such, the following provides a detailed methodology behind the construction of the platform and the different considerations behind certain decisions.

2.1 Mechanical

The response of the Stewart Platform is derived through the geometry of the platform and as such the first consideration to be made is the mechanical attributes associated with building the platform.
The structure separated into the most basic components consists of:

1. top plate
2. bottom plate
3. 3D printed struts
4. v-shaped cantilevers
5. mounting plate
6. spring
7. modified hollow banjo bolt joint
8. wire tighteners
9. wire

This list is not all-inclusive, leaving out ordinary fasteners such as nuts and screws but is sufficient in detailing the key components incorporated in the structure.
2.1.1 Plates

Starting with the structural support elements, Fig. 2.2 displays the general design of the platform’s top and bottom plates. A more detailed schematic of each plate may be found in Appendix B.

(a) Top Plate

(b) Bottom Plate

Figure 2.2: The design of the platform’s top and bottom plates

Both of the platform’s plates are designed to be created in a 3D printer, similar to the approach in [39]. The reasoning behind this is to reduce cost of manufacturing and repair. The top and bottom plates cover the entire breadth of the platform in order to provide a sound foundation and hold the active components. Initial attempts to create the top and bottom plates utilized multi-layered balsa wood, being relatively light weight and cheap with the multiple layers providing the structural support required. The process of manufacturing these pieces was found to be time consuming and required woodworking skills to maintain geometric precision.

To simplify fabrication, 3D printing was used to create the plates. Using 3D printing technology, the top and bottom plates are made within acceptable error tolerances. 3D printing allows damaged plates to be replaced with little cost and in a timely manner within tolerable margins of error.

While [39] does call for metallic printing material, all 3D printed components are fabricated from PLA. Since PLA is more abundant and inexpensive, the use of PLA helps to meet Criterion 6. Components made from PLA are rigid enough to hold the platform together with the appropriate geometry. While creep is a factor that will come into play eventually, the time spans associated with this concern are large enough to be handled through periodic replacing of the deformed plates and calibrations. This does mean that other components, such as the cantilevers, must be manufactured by separate means.
The top plate is circular, while the bottom plate is a hexagon. The circular design of the top plate was chosen to easily interface with the membrane holder designed for the suturing simulator. The bottom plate could be cylindrical as well but would use far more material than the top plate for little to no gain. The positions of the holes for mounting the components are dictated by specific geometric constraints, which will be discussed later, so any addition of space outside that required for mounting the components is unnecessary. Therefore, since the shape formed by the arrangement of the cantilevers on the bottom plate form a hexagon, the bottom plate is fabricated in this shape which saves in the cost of materials used and printing time required.

The reason why the base plate must be larger than the top plate, as seen in [33] and [41], is that the angles of the legs connecting the two plates have major ramifications to the response of the design and can bias the platform’s response in certain directions.

In order to avoid biasing the platform’s response in certain directions, the platform’s design should be equally stiff in all directions. Stiffness in this sense relates to the platform’s resistance to translations and rotations enacted on the platform and is characterized by the unit N/mm. The stiffness of the platform to these movements is inversely related to the sensitivity of the platform to the forces and torques which cause these movements. As such, if the platform exhibits equal stiffness to translations and rotations on all axes, then the platform will be equally sensitive to forces and torques along and around all axes. To ensure that the platform is equally stiff in all directions, a model of the stiffness of the platform was developed in [4].

To summarize the computation of the model in [4], the equation of equilibrium of the platform under an external load \( w_e \) is defined as:

\[
J f + f_0 S_0 + w_e = 0
\]  
(2.1)

where matrix \( J \) is constructed from the six screws of zero-pitch along each leg \( S_i \), \( S_0 \) is the screw of zero-pitch along the central column, and \( f_i \) is the magnitude of force applied over the legs and strut respectively.

Screws such as \( S_i \) and \( S_0 \) are normally used to model movements in rigid bodies and are
defined as:

\[
S = \begin{bmatrix}
  x \\
y \\
z \\
\alpha \\
\beta \\
\gamma \\
\end{bmatrix}
\]  \hspace{1cm} (2.2)

where \(x, y,\) and \(z\) form a unit vector along the axis of the rigid body while \(\alpha, \beta,\) and \(\gamma\) are the moments of the unit vector about the origin. For use in this paper, the screw representations of the platform’s six legs and the column are found to be line vectors which model the path and location of the legs and column. For example, the screw representation of the central column is defined as \(S_0^T = [0 \ 0 \ 1 \ 0 \ 0 \ 0]\). The line vectors are used to provide the direction of force on the legs and strut when under an applied force magnitude.

The model goes on to relate forces on the legs and strut to the axial elastic extension enacted on each through the equations:

\[
f = -K u
\]  \hspace{1cm} (2.3)

and

\[
f_0 = -k_0 u_0
\]  \hspace{1cm} (2.4)

where \(K\) is the diagonal stiffness matrix of the legs and \(k_0\) is the stiffness of the strut. The assumption that all legs exhibit equivalent stiffness allows \(K\) to be written as an identity matrix multiplied by the scalar unit \(k_1\).

The axial extension of each leg is defined by equation:

\[
u = J^T \Lambda T
\]  \hspace{1cm} (2.5)

where the six element vector comprising the axial extension of each leg \(u\), is related to the leg screw matrix \(J\), the elliptical polar operator \(\Lambda\), and the platform’s twist \(T\).

A similar axial extension of the central strut is defined by the equation

\[
u_0 = S_0^T \Lambda T
\]  \hspace{1cm} (2.6)
Through the use of Eq. 2.1, 2.3, 2.4, 2.5, and 2.6, [4] finds the global stiffness matrix modeled in the equation

\[ w_e = (JKJT + k_0S_0S_0^T)\Delta T \] (2.7)

where the stiffness matrix is influenced in one part by the stiffness of the legs \( JKJT \) and in another part by the stiffness of the strut \( k_0S_0S_0^T \). As the platform’s twist \( T \) is directly related to the measured strains, this composite stiffness matrix allows for the platform to be optimized for sensitivity to forces and torques by manipulating the platform’s resistance to translation and rotation.

The transformed leg stiffness matrix \( JKJT \) is defined as:

\[
JKJT = \frac{k_1}{a^2 + b^2 - ab + h^2} \begin{bmatrix}
  c_1 & 0 & 0 & 0 & c_2 & 0 \\
  0 & c_1 & 0 & -c_2 & 0 & 0 \\
  0 & 0 & 6b^2 & 0 & 0 & 0 \\
  0 & -c_2 & 0 & 3b^2h^2 & 0 & 0 \\
  c_2 & 0 & 0 & 0 & 3b^2h^2 & 0 \\
  0 & 0 & 0 & 0 & 0 & 9b^2h^2/2 \\
\end{bmatrix}
\] (2.8)

where, as seen in Fig. 2.3, \( a \) is the radius between the center of the bottom plate and the point of contact with the \( i \)th leg, \( b \) is the radius between the center of the top plate and the point of contact with the \( i \)th leg, \( h \) is the distance between the top and bottom plates from where the intersection of two adjacent legs occur, \( k_1 \) is the stiffness of each leg, and \( c_1 \) is a further relationship with:

\[ c_1 = 3(a^2 - ab + b^2) \] (2.9)

being the shear stiffness of the platform and

\[ c_2 = 3bh(a - 2b)/2 \] (2.10)

being a coupling factor.

The matrix \( JKJT \) models how the the parameters \( a, b, \) and \( h \) are directly related to the relationship between the platform’s twist and the forces and torques enacted on it with respect to the platform’s legs. Interpreting the matrix as the combination of four 3x3 submatrices, the first
diagonal submatrix models the resistance of the platform to translation while the second diagonal submatrix models the resistance of the platform to rotation. This means that the diagonal of matrix $JKJ^T$ defines how the forces exerted on the platform directly relate to the translations experienced by the platform and the torques exerted on the platform directly relate to the rotations experienced by the platform. The model implies that forces of similar magnitude applied along either shear direction will translate the platform similar distances while torques applied around either shear direction will rotate the platform to similar angular distances. The presence of off-diagonal elements indicate that a relation also exists between applied forces and rotations and applied torques and translations. For example, the model implies that a shear force in the x-direction is directly related to a translation in the x-direction ($c_1$) and a rotation around the y-direction ($c_2$). The only elements that appear not to be affected by multiple twists are forces along the normal and torques around the normal.

Based on the relation expressed in Eq. 2.8 and using the parameters in Fig. 2.3, a guideline to manipulating the stiffness of the platform, and thus the sensitivity, is presented as the relationships between geometric properties found in the structure of the platform. To maintain equivalent stiffness in all directions, the platform must be manufactured such that the diagonal of the matrix $JKJ^T$ contain numerically similar elements. The expression in Eq. 2.8, however, reveals off-diagonal elements which indicate that loads exerted on the platform are dependent not only on the direct relation between forces and translations in a certain direction and between torques and rotations.
in a certain direction but also the indirect relation between forces and rotations and torques and translations. In order to prevent this, the off-diagonal elements, $c_2$, are desired to be trivial in an ideal scenario. As seen in Eq. 2.10, these coupling factors are influenced by the radial distance of the intersection of two legs from the center of the top plate $b$ and the bottom plate $a$ and the vertical distance between these two intersections $h$. As all parameters must be non-trivial, parameters $a$ and $b$ are the most reasonable parameters to optimize. Eq. 2.10 states that if the parameter $a$ is set to twice the size of the parameter $b$, then the result is an off-diagonal element $c_2$ which approaches zero. This produces a modified model of the stiffness matrix with respect to the legs as:

$$JKJ_{\text{couple-f\acute{e}e}}^{T} = \frac{k_1}{3b^2 + h^2} \begin{bmatrix} 9b^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 9b^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 6b^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3b^2h^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 3b^2h^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 18b^4 \end{bmatrix}$$  \hspace{1cm} (2.11)

The modified model does not exhibit any coupling of forces and torques with rotations and translations respectively. As parameter’s $a$ and $b$ are now constrained by each other, the modified stiffness matrix in Eq. 2.11 is expressed in terms of parameters $b$ and $h$ with the parameter $a$ calculated with respect to $b$. This allows the modified stiffness matrix to be easily implemented when optimizing for the suturing system as $b$ will affect the amount of space available for unobstructed access to the stitching membrane both from above and below. Thus, the reason for manufacturing a bottom plate much larger than the top plate is to ensure that parameter $a$ is twice the magnitude of parameter $b$. In other words, the platform’s six legs should be oriented such that the intersection between two legs on the plane of the bottom plate occur at twice the distance from the center of the device as the intersection between two legs on the plane of the top plate.

The expressions on the diagonal of Eq. 2.11 when combined with the constraint on parameter $b$ from the suturing system over-define the model. This means that while forces and resulting translations and torques and resulting rotations are linearly independent of each other, the platform can not be constructed such that perfectly equal stiffness is observed in all directions.
2.1.1.1 Compliant Columns

Figure 2.4: The platform’s top and bottom plates connection to the compliant columns

Figure 2.5: 3D printed strut for compliant columns

In [4], the wires used for the platform’s legs are not rigid. While this benefits the platform by not transmitting torque along the legs, the legs cannot support the weight of the top plate. Therefore, a spring is introduced into the design and mounted in the center of the device which acts as a compliant support column. The compliant column places the wires in tension so that the legs are strained while the platform is at rest. This allows the platform to measure downward normal loads, which will reduce the strain measured on the legs. The platform is able to measure downward loads up until enough force is applied to counter-balance the force exerted by the compliant column.
at which point the wires will go slack. The addition of the compliant column allows the platform to measure forces and torques in both directions along all axes from the resting position. The compliant column is connected to the top and bottom plates by ball joints so as to minimize the impact of the column in shear directions.

As seen in Eq. 2.7, the overall stiffness matrix is comprised of both the leg stiffness matrix $JKJ^T$ in Eq. 2.8 and the stiffness matrix of the central column which [4] defines as:

$$k_0S_0S_0^T = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & k_0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix} \quad (2.12)$$

where the spring constant of the compliant column is $k_0$. The model of the compliant column’s effect on the stiffness of the platform in Eq. 2.12 states that the column only contributes to an increase in the platform’s resistance to translations in the normal direction.

The main problem with the proposed configuration in [4], when compared to the suturing system’s requirements, is the location of the compliant column. As the compliant column in [4] is situated in the center of the platform, a large volume of the platform’s interior is occupied. The loss of this space presents two problems. The first problem is that the suturing system camera’s line of sight to the stitching membrane will be obscured. The current camera is also centrally located which presents issues with mounting both the camera and the compliant column. The second problem is that, as the compliant column must connect to both plates of the platform, the top plate must be designed such that a solid structure exists in the center of the top plate. This solid region must also connect to the rest of the top plate so all the top plate exists as a single rigid body. Solid structures in the center of the top plate will further obscure the camera’s line of sight to the membrane and will reduce the area available for stitching on the membrane.

To overcome this problem, an alternative design is proposed in which a group of three smaller compliant columns are situated around the platform.

As noted in Sec. 2.1.1, the membrane used in the suturing system places a constraint on the
parameter $b$, the distance between the intersection of two legs on the plane of the top plate from the center of the platform, from Fig. 2.3. Since $b$ defines the radial limit of the platform’s unobstructed interior region, the value of $b$ must be greater than the radius of the membrane’s active stitching area to avoid obscuring the membrane from the camera and limiting the area of the membrane which can be used. By using the value of $b$ as the minimal distance a component can be placed near the center of the platform, the three compliant columns of the proposed design are situated in a radially symmetric pattern around the center of the platform at a distance of $b$. The design produced is similar to the supporting structure surrounding the 6D mouse in [9]. Since the equivalent spring constant is the summation of the individual springs in parallel configurations, the springs chosen for the three compliant columns must have lower stiffness as compared to the original.

The range of externally applied forces the structure may undergo before the pre-tensioned wires go slack is determined by the amount of load placed on the platform during construction. As this load is determined by the distance the springs are displaced from the neutral position $\delta$, tensioning will involve displacing the springs a set amount of distance to counteract the range of forces expected to be exerted. The relationship for this tensioning method when taking into account the geometry built into the platform is stated in [4] as:

$$\delta > \frac{1}{k_0} s_0^T f$$

(2.13)

where $\delta$ is the desired displacement of the spring, $s_0$ is the screw along the compliant columns, and $f$ is the externally applied forces and torques.

Assuming $k_0$ in the modified design to be the equivalent summation of the three springs and using the criteria described in 1.1, the platform is pre-loaded to resist up to a maximum of 30N in the normal direction by displacing the springs a distance of no less than 0.2mm.

The springs chosen for the compliant columns are able to accomplish this with one further alteration from the design seen in [4]. While the sensor in [4] is designed to handle a wide range of forces, the actual sensor constructed is tiny, with the recorded height of the device $h$ being 49mm. The dimensions of the device in [4] are too small for the platform’s purpose in the suturing system. The vertical distance between the intersection of adjacent legs $h$, based on the model in Eq. 2.11, is still a free parameter so $h$ is chosen to be the distance of the camera to the membrane on the original suturing system, which corresponds to the camera’s focal length.
The springs chosen for the platform extend 18mm at rest, but the suturing system requires that the platform is designed to be over 100mm tall. Since the springs are too small to bridge the distance of $h$, 3D printed struts are erected on the bottom plate to mount the springs. The struts, which can be seen in Appendix B.3, are designed to connect to the bottom plate and provide a stable mount from which to bridge the distance required by $h$. By incorporating the struts into the compliant columns, the springs can connect to the top plate and be displaced the necessary distance. The struts are fabricated separately from the bottom plate in order to modularize the design and decrease the amount of work necessary to replace a broken piece. As seen in Fig. 2.4b, a radially-symmetric group of three counter-bored holes are present on the bottom plate. This allows the strut to rest inside the bottom plate as a peg while the top plate only incorporates a donut-shaped indentation for the spring to rest inside. The top of the struts connect to the bottom of the springs with a small raised tab to keep the column aligned while tightening the platform. The tensioning process then locks these elements in place making any undesired movement in the column’s components difficult to induce.

Relying on the platform’s ability to lock the structure together encountered two problems. The first problem is that due to the low static friction force observed between the metal springs and PLA struts, the compliant column did not act as a single rigid body. This allows the springs and struts to move independently of each other while compressed. The second problem is that the connection between the holes of the bottom plate and the struts are loose due to dimension errors in the printing process. These two problems resulted in compliant columns which exhibited an ability to move a small amount. While the amount of movement is not enough for the platform to fall apart, the platform is observed to slightly change in geometry from before a load is applied to after the load is removed. To solve for this issue, epoxy is applied to the connections between the bottom plate and the strut, the strut and the spring, and the spring and top plate. The epoxy used is an off-the-shelf brand 5-minute fast drying epoxy. This same epoxy is also used in constructing the cantilevers and will be discussed later in Sec. 2.1.1.3.

Unlike in [4], the columns are not connected by ball-joints to the top and bottom plates. This will increases the columns' effect on off-diagonal elements which are not modeled by the stiffness matrix in Eq. 2.12. While this is deemed to be problematic, this paper will neglect the contribution this factor introduces into the platform's stiffness. The reasoning behind this is that the compliant columns’ springs act similar to a flexure joint and therefore reduces the effect caused by the more
Finally, to prevent bias in directional sensitivities resulting from the contribution of different stiffness in each column, all three compliant columns must use equivalent springs and equivalent strut designs.

### 2.1.1.2 Top Plate Joints

Figure 2.6: The top plate’s connection with the modified banjo bolt joint
Continuing with features observed in the top plate, three through-holes arranged in a radially-symmetric pattern around the center of the top plate are included in the design. These holes are where adjacent legs meet on the top plate and are placed at a distance of $b$ away from the center as seen in Fig. 2.3. As in [4], the legs are wires and are connected to the top plate by means of a screw. Since [4] never mentions how this is achieved, the approach used here is similar but not exactly the same. While the wires are discussed in more detail in Sec. 2.1.2, the wire used in the platform’s legs is thin piano wire.

The joint connecting the legs to the top plate is made with a hollow banjo bolt, commonly used in automotive applications. This type of bolt is characterized by a threaded vertical-bore down the center of the bolt and a horizontal through-hole below the head which intersects the vertical-bore perpendicularly. The bolt is designed to be fixed to the top plate at the holes seen in Fig. 2.6. This is done by inserting a bolt into each hole from underneath the top plate and using a nut above the top plate to hold the bolt up. From this upside-down position, a screw is inserted into the head of the bolt from underneath. When this screw is tightened, the horizontal through-hole is closed by the screw. This action grips the wire running through the horizontal through-hole fixing the wire in place.

The bolt performs two roles in the platform’s design: tightening the wires and fixing the wires in place.

To tighten the wires, the nut holding the bolt up is used to pull the bolt through the top
plate. By pulling the bolt upwards, the wire running through the bolt will be tensioned. Raising the joint will also reduce the distance between the top and bottom plates causing displacement in the compliant columns. By using a continuous segment of wire for pairs of legs, the process of placing the platform into tension is simplified to tightening the three nuts on the top plate.

While this guarantees that pairs of legs will be subjected to equivalent strains, which will simplify computations discussed later, the distribution of tension throughout the wire is also problematic. As the legs in this configuration will always exhibit the same strain, the condition of linear independence in each leg is violated. The violation of this condition will produce a platform that is unable to discern differences in magnitudes and directions of different forces and torques enacted on the top plate.

As such, the second role of the bolt, to fix the wire in place, remedies this violation. The wire is fixed in position by using the tightening screw to grasp onto the wire running through the horizontal through-hole. By using the tightening screw to constrain the wire at a fixed point, the single segment of wire maybe modeled as two independent legs. As the legs are now able to experience different strains, the condition of linear independence is met.

Thus, the two-stage process of tightening and fixing the wires with the bolt simplifies the act of pre-tensioning the platform during construction.

While the tightening phase experiences few issues, the wire frequently broke when manipulating the tightening screw to fix the wire in place. Examination of the wire and joint revealed two probable causes. First, the design of the bolt allowed the tightening screw to push the wire into the vertical bore. If the tightening screw pushed the wire too far into the vertical bore of the bolt, the wire would be pinched between the walls of the bolt and the threads of the tightening screw. The wire could then be stretched past breaking when applying to much torque to the tightening screw. The other cause is the difference in materials used to make the bolt, the wire, and the tightening screw. While all three components are made of steel, the steel in the bolt and tightening screw is harder than the steel used for the wire. This lead to instances where, when the wire is in tension, the bolt and tightening screw will begin to cut into the wire.

To prevent damage to the wire, the banjo bolt is modified by two independent pieces both placed inside the vertical-bore called the "cap" and the "plug". These additions are used to prevent direct contact between the wire and both the bolt and tightening screw. The plug is placed inside the vertical bore so as to cover half of the horizontal through-hole through which the wire travels. The
presence of the plug prevents the tightening screw from pushing the wire further into the vertical bore. The cap is placed on the tip of the tightening screw inside the vertical bore. The cap is made from a softer material than the wire which prevents the cap from cutting into the wire.

The cap and plug are created from brass screws. The plug is fabricated by shaving a screw down to a smooth brass rod slightly bigger than the vertical-bore of the hollow banjo bolt. The cap is manufactured by cutting and smoothing a small tab of a brass screw nearly as big as the vertical bore and rounding off one of the ends.

With these pieces in place, the modified banjo bolt joint is made through the following steps.

Steps

1. Grease the end of the tightening screw
2. Tighten the screw into the top of the bolt until the screw obscures half of the horizontal through hole
3. Apply JV-Weld around the plug and the rim of the bolts unoccupied end
4. Push the plug into the vertical bore until it comes into contact with the tightening screw and obscures the rest of the horizontal through hole
5. Wait one day to cure
6. Remove the tightening screw
7. Cut a small slanted notch into the horizontal bore on the bottom of the side not covered by the plug
8. Place the rounded head of the cap onto the tightening screw and insert both into the unoccupied end of the vertical bore hole.

The wire is inserted through the horizontal through-hole between the cap and plug. Tightening the tightening screw results in the wire being clamped between the cap and plug which creates the fixed point along the wire segment. As the cap and plug are both made of softer material than the wire, the wire is able to cut into the cap and plug without being damaged in the process. The notch is used to provide clearance between the bolt and the wire when under tension. The inclusion of the notch ensures that the modified joint can grasp onto the piano wire without damaging the wire.
2.1.1.3 Cantilever Mount

As seen in Fig. 2.8, three groups of four holes are placed near the outer rim of the bottom plate. The purpose of these holes is for mounting the cantilevers, which are discussed in detail in Sec. 2.1.3, onto the bottom plate.

In [4], each cantilever is fabricated such that the instrumented portion of the cantilever is thinner than the inactive portion of the cantilever. By creating more flexible regions where the strain gauges are located, the cantilever limits flexing to regions being measured while avoiding deformation in static regions.

For a similar effect, the mounting plate, in Appendix C.2, limits flexing to the active portion of the cantilever. A cantilever is positioned in the center of each group of holes under the mounting plate. The mounting plate is then fastened to the bottom plate at each corner. The cantilever is gripped between the mounting plate and the bottom plate which locks the cantilever into the correct orientation. As the mounting plates are made from the same material as the cantilever, any portion of the cantilever underneath the mounting plate is essentially doubled in thickness. Thus, the mounting plate is designed to cover all inactive areas of the cantilever to limit flexing to instrumented portions. This approach achieves the same result as the cantilever seen in [4] while
being easier to fabricate.

The mounting plate also provides a solid foundation near the cantilever to mount electronics, which will be discussed later in Sec. 2.1.5.

2.1.2 Legs

As previously mentioned, a primary deviation from the standard Stewart Platform design shared between [4] and the current platform is the use of non-rigid wires in the legs. While the wires are unable to support the weight of the top plate, requiring the compliant columns discussed in Section 2.1.1.1, the use of non-rigid wires in the legs provide a myriad of benefits.

First, as wires only transfer forces while under tension, the use of wires in the design allows for the sensor to be constructed with a built-in limiting factor for overload protection. For instance, testing of the suturing system reveals that the platform is expected to see a range of forces between $\pm 30\text{N}$ during operation. Therefore, if the platform is placed under a tension of $31\text{N}$ at rest, the range of forces expected during normal operation will be between $1\text{N}$ to $61\text{N}$. While the platform maybe stretched over $61\text{N}$, only $1\text{N}$ more of compression will produce a reading. After the $1\text{N}$ of leeway is exceeded, the wires will go slack and not transmit any more force to the cantilever. The ability of a wire to mechanically disengage at a certain threshold of force is useful for building overload protection into the platform. Since the wire will only mechanically disengage when subjected to a compression force larger than the magnitude of tension in the wire, the legs must be situated so the likely direction from which an overload load may originate will produce a compression. As stated previously, the most likely direction for an overload to originate from is the negative normal direction on the top plate.

In the original Stewart Platform, universal joints are used to attach the legs to the top and bottom plates. These joints allow the Stewart Platform to move each linear actuator independently by allowing other legs to reorient in response rather than deform. The joints also allow the Stewart Platform to be manipulated without too much energy being wasted due to friction. When a Stewart Platform is utilized as a sensor, the frictional force observed between the rigid legs and the top and bottom plates contribute to non-linearity in the readings. Therefore, Stewart Platform based sensors also commonly incorporate universal joints into the connection between the legs and plates. In either case, universal joints allow for the legs to deform independently of each other and reduce the effect of friction. However, as seen in Section 1.2.1, all mechanical joints still exhibit some
amount of frictional force which will influence the response of the sensor. Using non-rigid legs allows the platform bypass this phenomenon completely. As the wire does not resist deformation, the legs do not need to incorporate mechanical joints to allow for reorientation. Since the joints connecting the legs to the top plate, as seen in Section 2.1.1.2, and the cantilever, a brass crimp, are static entities, hardware which allows for movement in rigid bodies is absent. This benefits the platform by removing the primary cause of friction loss in other Stewart Platform designs.

2.1.2.1 Wire Tightener

![Figure 2.9: The apparatus used shorten the wires of each leg](image)

As the process of attaching the wire to the cantilever produced wire segments of unequal length, the platform requires a means to modify the length of each leg to produce a leveled top plate. The wire tightener apparatus seen in Fig. 2.9 is introduced into the design to accomplish this task. The wire tightener corrects the existence of excess wire left over from installing the wires onto the cantilevers by deforming the wire. While the line-of-action of the overall leg is kept, the path traveled by the wire is increased, which in turn decreases the effective length of the leg. As stated previously, the design of the legs have no effect on the response of the platform so long as the legs maintain the geometry required by the platform. The apparatus is able to deform the wire in any manner so long as this deformation does not change the intersection points of the leg. The two horizontal screws seen in the design grasp the wire preventing the apparatus from slipping. These screws also hold the wire to allow the deformation to occur in the region between. The vertical screw is used to push a metal plate located in the channel of the apparatus. When the vertical
screw is tightened, the plate will push the segment of wire between the two horizontal screws out of alignment. This decreases the amount of wire utilized along the line-of-action while maintaining the direction of the line-of-action.

By utilizing the wire tightener and the modified banjo bolt for each pair of legs, the six legs are fixed to exhibit the same length and same tension along that length.

### 2.1.3 Cantilever

![Figure 2.10: The v-shaped cantilever design](image)

As the three cantilevers are the only instrumented components in the platform, the design, shown in Fig. 2.10 must be manufactured with far more specificity than the platform’s other components. The design of the cantilever is also further constrained by the design choices throughout the rest of the platform.

For instance, [4] defines the relation between the external loads applied to the platform and
the forces observed on the \( i \)th leg as:

\[
\begin{bmatrix}
F_x \\
F_y \\
F_z \\
T_x \\
T_y \\
T_z \\
\end{bmatrix} = - \left( J + \frac{k_0}{k_1} S_0 S_0^T J^T \right) f
\]

(2.14)

where \( J \) is the matrix comprised of the screw representation of the six legs \( S_i \), \( S_0 \) is the screw representation of the compliant column, \( k_1 \) is the stiffness of each leg assuming all legs are equally stiff, and \( k_0 \) is the stiffness of the compliant column.

The relationship in Eq. 2.14 shows that the ratio between the stiffness of the compliant column and the stiffness of each leg is a factor which will affect the response of the system.

As the legs are composed of wires, specifically 1080 Spring Steel piano wire, which are chosen for high tensile stiffness, the effective stiffness of each leg is primarily determined by the cantilever. The reason why the cantilever will define the legs stiffness is due to the nature of connecting springs in parallel, which is assumed to be the condition present when connecting the wire to the cantilever. Since the equivalent stiffness obtained from this setup is defined as:

\[
k_1 = \left( \frac{1}{k_{\text{wire}}} + \frac{1}{k_{\text{cantilever}}} \right)^{-1}
\]

(2.15)

the high stiffness of the wire reduces the wire’s contribution to the legs stiffness when compared to the lower stiffness of the cantilever. In fact, the stiffness of the wire is so great that the wire’s effect is trivial to the system overall, being many magnitudes higher than the cantilever.

Therefore, the stiffness of a leg, is governed by the relation

\[
k_{\text{leg}} = \frac{E w t^3}{4 L^3}
\]

(2.16)

where \( E \) is the Young’s modulus of the material used in fabricating the cantilever, \( w \) is the effective width, \( L \) is the effective length, and \( t \) is the effective thickness. As parameters \( E \) and \( t \) are determined by the material used to manufacture the cantilever, in this case the Young’s modulus for steel with an effective thickness of 0.3in, \( w \) and \( L \) are the parameters more adaptable for optimization.
Since the sensor in [4] exhibits desirable responses, the ratio for the platform is designed in accordance with the ratio provided in that paper. As such, while the stiffness of the compliant columns and legs are not equivalent between the two systems, they are proportional with a ratio of 901/324 equivalent compliant column stiffness to leg stiffness. Thus, the width \( w \) and the length \( L \) of the active portion of the cantilever must be constrained to fulfill this ratio with the springs utilized in Section 2.1.1.1.

A V-shaped cantilever design is chosen to maintain the relations with other components in the platform.

As stated previously in Sec. 2.1.1, in order for equivalent stiffness, and thus sensitivity, in all axes to be maintained, the geometry of the platform must have the parameter \( a \) be twice the value of the parameter \( b \), from Fig. 2.3, in accordance with relations seen in Eq. 2.8 and Eq. 2.9. Usually, this is achieved by setting the joints connecting the legs to the plates at these positions. However, while this is true for the top plate, it is not practical for the bottom plate. In the platform, the cantilevers must act as the joints for the bottom plate in order to effectively measure the tension placed on the wire. As two adjacent legs must converge at this location, the cantilevers physically can not reach these points without overlapping and interfering with other cantilevers

This dilemma is solved by the fact that only the line-of-action in the legs must intersect at these points. As long as the unit direction of each leg exhibit this virtual geometry, actual mechanical connections are unnecessary and only ensure this constraint is kept. Thus, the angles in the cantilever’s design are optimized to intercept the wire along this path. By keeping the virtual lines-of-action intersecting within the plane of the bottom plate at a distance of \( a \), the cantilever’s may bare the full load applied to the leg without the interfering with each other. This is also the reason, as described in Section 2.1.1, the bottom plate may be reduced in size. Because a physical joint is unnecessary at the points of intersection, the bottom plate does not need to extend to include the points of intersection in the rigid body.

In order to intercept the legs at the correct position, the bent angle of the cantilever \( \phi \) and the effective length \( L \) must be optimized with the non-active length below the mounting plate. As \( L \) is also a parameter in determining the leg stiffness, in accordance with Eq. 2.16, further restrictions on the design and placement of the cantilever’s intersection with the wire are present.

As the cantilever is instrumented to measure for the strain induced by forces along the wire, the optimal position to measure this strain is near the bottom of the active area on cantilever which
is governed by the relation

$$\epsilon = \frac{6fL}{Ewt^2}$$  \hspace{1cm} (2.17)

where $\epsilon$ is the strain near the bottom of the cantilever caused by a normal force $f$ applied at a distance $L$ away.

The key to Eq. 2.17 is in the definition of $f$ as the normal force, which is the force applied perpendicular to the plane-of-action. Defining the angle generated by the intersection of the wire with the cantilever as $\theta$, Eq. 2.17 can be rewritten as

$$\epsilon = \frac{6Lf \sin \theta}{Ebt^2}$$  \hspace{1cm} (2.18)

From Eq. 2.18, $\epsilon$ is non-linearly reduced as the force veers from the normal direction. This will correspond to a non-linear loss of sensitivity in the strain sensing elements on the cantilever. As such, the cantilever is most effective when maintaining a perpendicular intersection between the plane of the cantilever’s active area and the direction of the wire. Deviations from the perpendicular intersection will introduce non-linear reductions in the measurements.

Therefore, the dimensions seen in Appendix C.1 are optimized based on all the above conditions.

2.1.4 Strain Gauge

As the cantilevers are the only components on the platform which are instrumented with electronics, the method by which the strain gauges are chosen and mounted to the cantilevers must be handled with care.

The strain gauge chosen for the platform is the SS-060-040-2500PM-S1 M-Shaped Semiconductor Gauge manufactured by Micron Instruments. The gauge is un-backed, meaning the gauge lacks a substrate on which the active element rests on, which results in a thin structure that contributes a negligible stiffness to the cantilever.

The reasoning behind this choice is two-fold: space and response.

First, the active length of the gauge is around 0.040in, which contributes a small footprint when mounted onto the cantilever. This allows the cantilever’s dimensions, most notably width $w$ and length $L$, to be unconstrained by the dimensions of the gauge. The small size allows for
mounting the gauge closer to the ideal position expressed in Eq. 2.17 which will result in more sensitive readings.

As for response, the gauge is rated with a Gauge Factor of around 140±10. As gauge factor is defined as:

\[ G.F. = \frac{(R - R_m)}{RE} \]  \hspace{1cm} (2.19)

where \( R \) is the nominal un-strained resistance and \( R_m \) is the measured resistance under strain \( E \), for every unit of strain detected, the strain gauge will output a change in resistance 140-fold greater making the gauge extremely sensitive. As the platform must measure the forces exerted by a needle on a membrane, a highly sensitive gauge is necessary in the platform. The increased sensitivity not only aids in detecting tiny variations in the induced strain but also aids to compensate for any flaws present in the platform that made the transference of these strains from the applied force suboptimal. For instance, while all attempts are taken to ensure that each wire intersect the cantilever perpendicularly, in keeping with Eq. 2.18, the leg still applies some of the aggregate force in the parallel component relative to the cantilever as the angle \( \theta \) is anywhere between ±4 degrees off.

Thus, by implementing a highly sensitive gauge that is mounted to the cantilever close to the base of the active area, errors in other components may be mitigated.

As for mounting the gauges onto the platform the following materials and steps are undertaken:

Materials:

- 2 SS-060-040-2500PM-S1 Gauges
- 1 V-Shaped Cantilever
- 1 vial of silver conductive paint
- 1 sheet of paper
- 1 bottle of 5-minute epoxy (also used in Section 2.1.1.1)
- 3 electrical wires
- 1 roll of thin double-sided tape

Preparations:
Prepare a mask from the paper to be used for the application of epoxy layers. The mask shall be a sheet no wider than 1in with a square cutout 1cm in size located near the top. The length of this sheet shall be around the same size as the cantilever’s active area which is to be instrumented.

The cantilever’s active area is to be polished and cleaned to remove any debris that might otherwise inhibit the bonding process.

Steps:

1. Apply a thin coating of epoxy over the entire active area of the cantilever to be instrumented

2. Wait one day to cure

3. Once cured set the paper mask such that the cutout is located in the desired mounting position and apply a layer of epoxy to this area using a straight rigid edge to wipe away the excess leaving a paper thin layer in the shape of the cutout

4. Wait around 5 minutes for this layer to begin solidifying

5. Apply the gauges to the layer such that one gauge is pointing to the top of the cantilever while the other is oriented perpendicular to the first gauge making sure all but one lead from each do not intersect. The gauges should rest on top of the epoxy layer with the leads left free to move to an extent

6. Wait one day to cure

7. Braid the leads of the two intersecting wires together and apply a coat of silver paint to this connection

8. On one side of the cantilever, apply a strip of tape and position three electrical wires which have been braided together on the tape such that the insulation holds onto the tape while leaving a bit of exposed wire over the cantilever

9. Take the three leads over to the attached wires wrapping the remaining lengths around the wire before applying a coat of conductive paint over the joint

10. After waiting for the acetone in the paint to evaporate, apply epoxy over the path of the leads and the wires making sure to envelope any joint connected with the conductive paint

11. Apply a thin coat of epoxy on top of any exposed surface of the strain gauges
12. Wait one day to cure

13. After ensuring that the gauges and wires are embedded firmly in place, create a fastener out of a thick copper wire to fasten the braided wires to the back of the cantilever after wrapping them around the edge

14. Repeat for the other-side of the cantilever making sure the braided wires end up on the same side as each other

The process takes three days at minimum to complete and results with three V-shaped structures with six active sensing areas between them.

The three layers of epoxy applied in the process each fulfill a role critical in the cantilever. The first layer of epoxy forms a non-conductive barrier between the leads of the gauge and the metal of the cantilever to prevent shorts. Precautions are taken before and after application of the first layer to keep the through-hole for the wire at the top of the cantilever clear and to avoid coating any portion of the cantilever other than the active area. The second layer bonds the strain gauges to the cantilever. Due to the gauge’s minuscule mass and size, applying the gauges directly after applying the second layer tends to fail as the gauges will float out of position or sink further than desired into the second layer of epoxy. This is the reason for the delayed period between applying the second layer of epoxy and introducing the strain gauges once the epoxy had begun hardening. As the epoxy layer is more viscous once hardening ensues, applying the strain gauges after the process starts becomes easier while still allowing for bonding to occur. The mask is used to reduce the amount of epoxy between the gauge and the metal. The mask also aids placing the strain gauges by constraining the area covered by the second layer of epoxy. The final layer of epoxy is a protective coat around the sensitive elements and acts to reinforce connections created with other bonding agents, such as the silver conductive paint. In testing different mounting procedures, the fragility of the gauge became apparent thus requiring the need for a protective element to prevent damage to the gauge. The protective layer is kept thin so as to minimize the amount of material used in the construction by applying the epoxy with a soft bristle paint brush. The protective layer also reinforced the connections between electrical wires to prevent forces applied to the legs from breaking the embedded gauges and leads.

As the strain gauges use solid gold leads, normal soldering material is ineffective. As most solders use lead, which is reactive to gold at high temperatures, using normal solders will result in
the destruction of the gauge’s leads. To connect the gauge’s leads to other electrical wires, silver paint is used to coat the joint created by wrapping the leads around wires. Since the paint is more conductive than equivalently priced conductive epoxies, the use of the paint as a bonding agent minimizes the change in resistance on each cantilever.

An issue with using the silver conductive paint is that the paint does not have enough bonding strength to hold the joints together when subjected to loads. Therefore, the connection is covered by the final layer of epoxy as a means of providing a more resilient bond. As the paint uses acetone as the carrier, the delay between applying the paint and applying the epoxy is present to allow any acetone that will weaken the epoxies bond to evaporate.

The clip fastening the cantilever’s electrical wires to the backside of the cantilever is included for two reasons.

First, while the cantilever’s electrical wires are embedded in epoxy, torque applied to the electrical wires will translate through the protective layer putting the connections between the wires and leads at risk. To provide relief for torques transmitted through the cantilever’s electrical wires, the wire is wrapped around the edge of the cantilever. This prevents the torque in the wire from interacting with the embedded gauges and leads. The clip is meant to maintain the bend of the cantilever’s electrical wires around the cantilever.

Second, if the cantilever’s electrical wires are left unconstrained on the platform, the electrical wires will contribute to noise in the readings. Since the wires used for the cantilever are small and flexible, external stimuli, such as bumping the suturing system, may induce vibrations in the wires. If the wire is allowed to transmit this vibration to the strain gauge, the readings from each cantilever will exhibit noise. By securing the cantilever’s electrical wires to the back of the cantilever, the effect of these vibrations are dampened by the cantilever’s stiffness.

While early versions of the cantilever used a quarter-bridge configuration, testing revealed a flaw in this design. During these early tests, outputs of the cantilever were observed to drift while the cantilever was unloaded. As the temperature of the cantilever appear to correlate with this drift, a change was made to compensate for the effect of temperature.

The current cantilever design’s strain gauges are oriented in a half-bridge configuration with temperature compensation. The active gauge is pointed along the length of deflection to measure the strains caused by deformation. The inactive gauge is pointed in the perpendicular direction to the active gauge to compensate for temperature fluctuations in the cantilever. As the inactive
gauge is unaffected by the direction of deformation in the cantilever, any changes measured on the inactive gauge is due to the result of changes in the cantilever’s properties, i.e. temperature. Used in conjunction with the measurements of the active gauge, the cantilever is able to separate the change in resistance caused by deformation in the cantilever from the change in resistance caused by environmental factors.

The gauges on each cantilever are not paired. This means that the two strain gauges in the half-bridge are not guaranteed to exhibit the same response to the same stimulus. As the gauges still exhibit equivalent properties, the effect of using un-paired gauges is negligible in the platform.

Finally, during construction of the cantilever’s, one lead from each gauge is joined together by the conductive paint. By fusing these leads together, each cantilever requires only three connections to interface with other equipment. The joined leads form the output of the cantilever’s side of the half-bridge while the two remaining leads provide the cantilever with a voltage supply and ground. This simplifies the interface with the cantilever but also prevents testing either strain gauge independently.

2.1.5 Internal Hardware

While the electrical wires used on the cantilever limit the effect of the wire on the response of the cantilever, the cantilever’s electrical wires are not suitable for connecting the cantilever with other equipment for two reasons.

First, the cantilever’s electrical wires are small and flexible due to a lack of insulation around the wire coupled with a small-gauge. While braiding the cantilever’s electrical wires does help to shield the low-voltage output, the cantilever’s electrical wires are still vulnerable to the addition of noise if transmitted long distances. As such, the electrical wire will add unnecessary noise into the platform if required to transmit the signal over a distance.

Second, while the cantilever’s electrical wires are flexible, the cantilever’s are sensitive enough to detect deformation in the wire. If the cantilever’s electrical wires are used to connect to equipment not rigidly linked to the platform, the platform will be able to measure loads applied indirectly through the cantilever’s electrical wire. Changing the relative position between the platform and the external equipment will also change the tension experienced in each leg if a direct connection is made. As braiding the cantilever’s electrical wires also increases the stiffness in the cord, a change in tension on the braid will cause the cantilevers on the platform to exhibit different
stiffness’ and tensions in each leg. Therefore, any connection made to the cantilever’s electrical wires must be static in relation to the platform’s rigid body.

As the platform underwent various changes during testing, most of the electronics of the platform, discussed in Sec. 2.2, are located off the platform for ease of access and safety. If the cantilever’s electrical wires are used to bridge the gap between the cantilevers and other electronics directly, the two issues of introducing noise and indirect loads will complicate the platform’s response. The other electronics are also connected through a breadboard in order to allow quick changes to be implemented during testing. The cantilever’s electrical wire is unable to form a stable connection to this breadboard due to the small gauge of the wire. As soldering the connection will defeat the purpose of implementing the breadboard in the first place, the cantilever’s electrical wires are not suitable for connecting with the breadboard. Also, as each cantilever requires three connections to interface with other equipment, making direct connections between the breadboard and the platform will require at least eighteen separate lines. This will further complicate the platform and make the design messy and unwieldy.

To solve these issues, the cantilever’s electrical wires are designed to interact with the platform’s outgoing connections through the use of a fixed terminal on the platform.

As discussed previously in Sec. 2.1.4, the mounting plates used to fasten the cantilevers to the bottom plate provide a stable foundation near the cantilevers to mount electronics. In future designs, the platform maybe self-contained by mounting all the electronics on the mounting plates. Currently, the mounting plate is used to terminate the cantilever’s electrical wires at a static point on the mounting block which facilitates the connection with the platform’s outgoing cord.

A strip of prototype board is fastened to the mounting block to provide the foundation for the junction between the cantilever’s electrical wires and the platform’s outgoing cord. Each of the cantilever’s electrical wires are fed through the prototype board and are soldered to header pins underneath. The platform’s outgoing cords are then attached to the header pins above the prototype board. The header pins use the prototype board as a brace to dampen applied loads at this junction. Thus, any loads transmitted through the platform’s cord must deform the rigid body of the prototype board to deform the cantilever’s electrical wires.

As stated previously, the platform requires eighteen connections in order to operate the six cantilevers. The number of connections required may be reduced by connecting terminals on each cantilever. By soldering the pins used to provide the voltage supply and ground to each cantilever
to the adjacent cantilever on the same mounting block, the number of connections necessary for each pair of legs is reduced from six to four. By connecting the power and ground pins on each mounting block to the other mounting blocks, the number of outgoing cords from the platform is reduced further. This simplifies the platform’s design by requiring eight connections instead of eighteen connections. While two of the outgoing cords are used to provide the voltage and ground to the platform, the six other outgoing cords are used to transmit the output of the six cantilevers.

2.2 Electrical

Since platform’s response is determined by the mechanical attributes described in Section 2.1, all electronics serve one of two purposes: supplying constant voltages or preparing the outputs for recording.

The electrical schematic in Fig. 2.11, gives a simplified view of the electrical setup of the platform. The overlaying box signifies elements of the schematic which are repeated for each cantilever. For example, the two 2.5kΩ variable resistors inside the overlaying box represent the strain gauges mounted on each cantilever.

As stated previously, the strain gauges are mounted onto each cantilever in a half-bridge configuration for temperature compensation. While a full-bridge configuration also provides temperature compensation as well as increased sensitivity, the sensitivity of the half-bridge configuration is sufficient for the platform. The choice of using a half-bridge configuration also reduces the man-
ufacturing cost and reduces the time required to fabricate the cantilevers.

During initial tests of the platform, changes in the voltage output of the cantilevers were observed when no forces were applied. Further testing revealed that the strain gauges exhibited a non-trivial response to ambient light. This response is observed as large fluctuations in the cantilever’s voltage outputs when the ambient light in the room is removed and then reintroduced. Smaller changes are also observed by obstructing ambient light when placed in the shadow of an object. As the methods of testing the platform required manual manipulation of objects on the platform and movement around the platform, the changes in ambient light on the cantilevers during testing affected the outcome of the tests. To fix this issue, the area where the strain gauges are mounted on each cantilever is covered with a single piece of black electrical tape. By blocking all ambient light from the strain gauges, the platform is able to function without being affected by changes in the surrounding lighting conditions.

The platform is powered with a BK Precision DC Supply Voltage Box. The negative terminal of the DC supply acts as the platform’s ground while the positive terminal acts as the voltage source.

A low-pass filter is used to eliminate any AC component present in the DC supplies signal. The low-pass filter, as seen in Fig. 2.11, is comprised of three electrolytic capacitors and one ceramic capacitor in a parallel configuration. The electrolytic capacitors are used to increase the capacitance value to reach the desired cutoff frequency. The ceramic capacitor compensates for the three electrolytic capacitor’s inability to eliminate higher frequencies of AC noise. While increasing the resistance in the filter will also decrease the cutoff frequency, testing revealed a significant increase in the voltage drop across the filter with increased resistance. For instance, if the low-pass filter used a 2.2kΩ resistor, a 9V source from the DC generator will be reduced to a 5V supply for the platform. Use of a large resistor in the low-pass filter also introduced a coupling response between the outputs of cantilevers. Whenever a voltage output from one cantilever exceeded the operational limit of the amplifiers, voltage outputs of other unloaded cantilevers changed in response. By decreasing the size of the resistor to 1Ω, the cantilever’s coupled effect is trivialized. The large voltage drop across the filter is also reduced by decreasing the resistance in the low-pass filter. The cutoff frequency of the supplies low-pass filter in the platform is approximately 39Hz.

The filtered DC supply is used to power the platform and all electronics. This includes both the active portion of the half-bridge on the cantilevers and the inactive portion of the half-bridge on the breadboard.
For the platform to function, an additional constant voltage value is necessary. The constant voltage must be half the value of the original voltage source. As seen in Fig. 2.11, a voltage divider is added after the low-pass filter to create the constant voltage required. A capacitor is connected in parallel to the grounded resistor in the voltage divider to stabilize the voltage output. As the operational voltage of the platform is 5V, the output of the voltage divider must be 2.5V.

Usually, the resistance values of the passive elements of the half-bridge configuration are equivalent and proportional to the nominal resistance of the strain gauges. This produces a 0V difference between the two sides of the bridge when no load is applied. The addition of load will produce changes in the resistances of the strain gauges due to deformation. Changes in the resistance of each gauge will cause subsequent changes to the measured voltage between the sides of the bridge. While this is the normal application of a bridge, the platform does not exhibit this relation.

Since the legs are placed in tension by the compliant columns while the platform is at rest, the resistance of the active strain gauge is not equal to the gauge’s nominal resistance. To account for the change in the active gauge’s resistance, the resistances in the passive elements of the half-bridge are chosen to be proportional to this new ratio, as seen in Fig. 2.11. By pre-biasing the ratio of resistance between the passive elements of the half-bridge, the voltage difference in the bridge is brought closer to equilibrium while the platform is at rest.

While pre-biasing the passive elements of the half-bridge does bring the bridge closer to equilibrium, the actual voltage difference on the bridge tends to vary between cantilevers. These variations between cantilevers are primarily due to dimensional errors when fabricating the components of the platform and during the platforms construction.

While each half-bridge can account for this by using different resistors, this approach presents a few issues. As the resistors are trying to compensate for the strain gauges, the resistance values of all twelve passive elements will need to be carefully handled to match each cantilever’s gauges. The resistance of all twelve elements will also need to be optimized each time the platform is deconstructed and reassembled to reflect the new tension on each leg. Using twelve different elements will also increase the cost of manufacturing each platform along with increasing the complexity in the platforms design.

Since the passive elements of each bridge connect to the same points in the circuit, the voltage supply and ground, the inactive portion of each half-bridge is created with two resistors that are shared between the different cantilevers. While this decreases the number of elements in
each bridge, the problem of variation in the strains measured on each bridge is still present. In order to allow for adjustments to be made for each bridge to account for the variations, a trimming-potentiometer is added to each cantilever to bridge the passive elements of the half-bridge as seen in Fig. 2.11. The addition of the trimming-potentiometer in each bridge allows the ratio between the two passive elements to be modified in order to reflect the proportions of the strain gauges on each cantilever. The trimming-potentiometer acts in the circuit to "tune" the voltage differences and achieve equilibrium in all cantilevers. By using the trimming-potentiometer, the platform is more adaptable to change and less complex than the design using twelve separate resistors.

An AD623BNZ instrumentation amplifier is used for each cantilever. The AD623BNZ is a two-stage amplifier, meaning that the two inputs of the amplifier are each run through separate amplifiers before being compared to each other. The AD623BNZ also features a built-in feed-back loop which simplifies the process of modifying the amplifier’s gain to a single choice of resistor. The voltage output from each cantilever connects to the negative terminal of the amplifier. The respective voltage output of the trimming-potentiometer connects to the positive terminal of the amplifier. The filtered DC supply is used to provide voltage and ground to the amplifier which defines the limits of the amplifier’s range. The output of the voltage divider is sent to the reference terminal to bias the output of the amplifier to half the allowable range. This sets the amplifier to output a signal between 0V to 5V with a resting output voltage of 2.5V. The gain for this sensor is set to around 454. At gains larger than 454, the platform’s response is too noisy.

The output from each amplifier is filtered in hardware by low-pass filters with a cutoff frequency of around 220Hz. This filters out high frequency components in the amplifier’s output which were magnified during amplification. All six of these signals are sent to a Quanser board’s 16-bit ADC to be recorded by the computer’s software.

The filtered signals are transmitted to the Quanser board by six shielded cables. Each cable consists of an inner conductive thread, used to transmit the signals, surrounded by an inner cord of insulation. A second conductive braid surrounds the inner insulation to provide shielding to noise pollution. This second layer is attached to the ground of the platform. The outer conductive mesh is surrounded by external insulation which encapsulates the cable.

As the DC supplies earthing ground is unused, the platform lacks a stable source from which to measure ground. To account for the lack of a true ground, the analog ground lug of the Quanser board is connected to the negative terminal of the DC supply. This allows the Quanser
to measure incoming signals with respect to the Quanser’s internal ground. This also prevents ground loops within the circuit of the platform from forming. Since the power supply used by the Quanser is connected to the wall outlet by an isolation transformer, the platform is protected against ground-loops formed outside the platform’s circuitry.

All of these precautions ensure the measurements obtained by the Quanser are unaffected by noise pollution from external sources.

2.3 Signal Conditioning

To record signals taken from the platform, a Quanser board is used for the data acquisition system to interface the platform with a computer. The computer runs a program constructed in the Matlab Simulink environment. The Simulink object run is displayed in Fig. 2.12.

As seen in Fig. 2.12, the program uses the Q8 Quanser Analog Input block to retrieve signals from the platform. The recorded signals on each channel of the Q8 Quanser Analog Input block are taken after the process of amplification and filtering discussed in Sec. 2.2.

Each of the Q8 Quanser Analog Input block’s channels are attached to a low-pass filter included in the Simulink model. The low-pass filter in the Simulink model is setup with a cut-off frequency of 50Hz. The inclusion of this low-pass filter in the software will be discussed in Sec. 3.1.

After applying the low-pass filter, the signals are adjusted with a summation block. The summation blocks perform a subtraction operation on each signal where each signal is reduced by a value provided by six constant value blocks. Each constant value block is labeled as Sensor $i$ Bias, where the $i$ designates the leg of the platform from which the signal originates. Each of the Sensor Bias blocks are set to a default value of 2.5V when the program starts but may change independently of each other during run-time. The reason behind this modification is discussed in Sec. 4.2.

After each signal is modified by the summation blocks, a serial bus is used to group the signals into a single data line. The signals are then recorded in the memory of the computer and passed as one of two inputs into a Matlab function block. A graphical display of each signal is generated by the computer in the top left of the monitor. A corresponding numeric table of each signal’s current value is also generated in the bottom left of the monitor.

The Matlab function block uses the modified signals with a 6x6 matrix provided by the constant value block labeled as Calibration Matrix. By combining both the Calibration Matrix
Figure 2.12: Matlab Simulink model used for displaying the input/output data surrounding the sensor as well as containing the necessary transformations and biases to calculate the output data.

and the six modified signals, the Matlab function block computes the equivalent forces and torques applied to the platform on each axes. The estimated forces are used to generate a running plot in the top right of the monitor while the estimated torques generate another plot in the bottom right of the monitor. The mathematical operation performed by the Matlab function block is discussed in Sec. 4.2
Chapter 3

Signal-Level Performance

This chapter details observed errors seen in the voltage outputs from the platform’s cantilevers. Sec. 3.1 focuses on the presence of noise in the cantilever’s outputs after applying the filter’s discussed in Sec. 2.2. The majority of this chapter is dedicated to Sec. 3.2 which discusses a slow transient response observed in the outputs of each cantilever. Sec. 3.2 goes on to discuss the origin of the slow transient response and possible modifications to solve for it.

3.1 Noise

This section discusses the presence of noise in the cantilever’s voltage outputs. To pinpoint the cause of noise in the voltage outputs, a sample of data from each signal is recorded while the platform is at rest. A spectral analysis of each signal is conducted with the results shown in Fig. 3.1. The section is used to justify the addition of the low-pass filters to each signal in the Simulink model of Fig. 2.12 in Sec. 2.3.

From comparing the different signals’ spectral density in Fig. 3.1, peaks are observed at 60Hz at levels deemed detrimental to the performance of the platform. While circuitry exists in the hardware of the sensor to diminish the potential causes of the 60Hz noise, the definitive solution to alleviate this problem is found in the addition of a single IIR low-pass filter in the software as seen in Fig. 2.12. The addition of a low-pass filter for each signal set with a cutoff frequency of 50Hz and an attenuation of -40dB reduces this issue to tolerable levels.
Figure 3.1: Sensor Noise without Software Low-Pass Filter as seen in Fig. 2.3
3.2 Visco-elastic Response

This section discusses the presence of a slow transient response to forces applied on each cantilever. While the cantilever exhibits a fast transient response when the load on the cantilever is changed, a slow transient response is observed to occur for long spans of time after the fast transient response. This section details experiments run to locate the origin of the slow transient response. The section then goes on to test potential solutions to solve the cause of the slow transient response.

Two types of responses are observed in the voltage outputs from each cantilever: a fast transient response and a slow transient response.

The plot in Fig. 3.2 will be the example used to explain the two response.

The first type of response observed is a fast transient response expected when adding or removing loads from the platform. The fast transient response is observed in Fig. 3.2 as a sudden change in the voltage outputs of all Sensors.

The second type of response is a much slower transient response observed to occur after the fast transient response. This slow transient response is observed in Fig. 3.2 as a change from the initial voltage value after the fast transient response. While all the Sensors present in Fig. 3.2 exhibit the slow transient response, S2 is seen to be the most effected. The slow transient response lasts long after the fast transient response has dissipated.

![Figure 3.2: Visco-Elastic Response in Sensor 2](image)

In addition to the slow transient response to changes in load, slow transient responses are observed immediately after tightening the platform’s legs during construction and when turning
the platform on for operation. For the former, this leads to an inability to use the platform for a considerate amount of time after finishing construction. For the latter, this leads to the necessity of allowing the platform to "warm-up" for a considerate amount of time after the power is supplied. If either of these conditions are not met, the trimming-potentiometers in Fig. 2.11 are unable to balance the half-bridge to a point where voltage readings from the amplifier are within operational ranges.

Testing the unloaded cantilevers reveal this to be a fault of the cantilever’s design rather than a fault in the geometry or fabrication of the platform’s other components as these issues appear whether or not the cantilever is connected to an object.

To reveal the cause of this anomaly, three new cantilevers are constructed utilizing different aspects of the original cantilever’s design. Each of these new designs utilize the same effective cantilever length of the original cantilever seen in Appendix C.1.

The information in Table 3.1 displays the thickness of the cantilevers’ different layers. This includes the measured thickness of shim used for constructing the cantilevers, the preparatory layer of epoxy on which the strain gauges are placed, and the covering layer of epoxy under which the strain gauges are protected. A change is also incorporated into the construction method of these new cantilevers in that aluminum foil is used for the epoxy masks rather than paper. The result of this change can be seen in the table’s preparatory layer thickness values as a reduction of this layer in new cantilever designs by nearly a magnitude. A point of note is that while the original cantilever used the same off-the-shelf 5-minute fast drying epoxy applied to the compliant columns in Sec. 2.1.1.1, the new cantilevers use a slower curing (24-hour) off-the-shelf epoxy.

Furthermore, while the original cantilever is bent at a 55° angle, these new cantilevers are prepared as flat plates.

As for the similarities between the new cantilever designs and the original cantilever design, each of the new designs have some aspect in common. The Large Wire design utilizes the same wires used in the original cantilever’s construction while minimizing the amount of glue holding things together. This forgoes any protection to the strain gauges and connecting wires. The only exception to this is the addition of epoxy to hold the joints between the gauge’s leads and the large wires as the silver paint is deemed too brittle to hold without this addition.

The Protected Wire design uses magnet wire instead of the Original design’s wires. This
design does include a protective coating above the gauges leads while leaving the active element of the gauge uncovered. This is why in Table 3.1, the cover layer value for this design is neglected. The Protected Wire design uses tape to better hold the flexible pieces and provide added buffer between the shim and the conductive elements like in the Original's design.

The Minimal design is the most different utilizing both the magnet wire and limiting glue only to the preparatory layer.

<table>
<thead>
<tr>
<th>Cantilever Name</th>
<th>Shim Thickness (mm)</th>
<th>Prep Layer (mm)</th>
<th>Cover Layer (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>0.62</td>
<td>0.10</td>
<td>0.30</td>
</tr>
<tr>
<td>Minimal</td>
<td>0.59</td>
<td>0.01</td>
<td>N/A</td>
</tr>
<tr>
<td>Large Wire</td>
<td>0.60</td>
<td>0.02</td>
<td>N/A</td>
</tr>
<tr>
<td>Protected Wire</td>
<td>0.59</td>
<td>0.02</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 3.1: Cantilever Design Attributes

All cantilevers are threaded with a fishing line through the built-in hole used to connect the platform’s legs. The cantilevers are clamped to the edge of a metal table under a metallic plated at around the same distance with a c-clamp. Masses are applied at the end of the fishing line which allows the mass to hang directly below the built-in hole except in the case of the original design. As the original design is bent at a 55° angle, the actual effective force applied by the mass is governed by the equation $MG\cos(55°)$ where $M$ is the mass applied and $G$ is the acceleration due to gravity.

Figures 3.3, 3.4, and 3.5 display measurements taken under these conditions when each cantilever is subjected to a load applied by a 20g, 40g, and 50g mass respectively. Each of these loads are applied separately from one another which accounts for the varying amounts of time recorded in each figure. Further irregularities observed between data sets of similar loads is the voltage range exhibited by the Original cantilever versus the other three new designs. This is due to the effective weight of an applied mass on the Original being reduced by roughly half when loaded. Since neither strain gauge of the half-bridge is positioned to measure strains caused by shear forces, the measurements are assumed to only be reduced in magnitude and unaltered by missing the missing component.

With those facts in mind, significant differences are observed in the Original cantilever’s responses, seen in Fig. 3.3a, 3.4a, and 3.5a, when compared to the other designs.
Figure 3.3: Different Cantilever Design Responses to 20g Applied Weight
Figure 3.4: Different Cantilever Design Responses to 40g Applied Weight
Parameters for each signal are computed and placed in Table 3.2. The drift error denotes the voltage difference between the average value from before the mass is applied and a one second interval at the end of the recorded signal. Settling time $T_{S,x}$ signifies the time taken for the signal to consistently be constrained to within 2 percent of the calculated range of the response starting from the maximum measured voltage. As each signal demonstrates two step-responses, one for applying the mass and one for extracting the mass, two values for settling time are computed with a 1 denoting the response for applying the mass while a 2 denotes the response for extracting the mass. Similarly, the time constant $T_{C,x}$ denotes the amount of time from the maximum measurement of the signal to reach 63 percent of the signals final value with the value of $x$ denoting whether the parameter is for applying or extracting the mass. As only the original cantilever’s output demonstrates a first-order response, the time constant is computed for the original’s response specifically while settling time and drift error are computed for all responses.
Table 3.2: Cantilever Step-Response Parameters

<table>
<thead>
<tr>
<th>Mass (g)</th>
<th>Cantilever</th>
<th>$T_{C,1}$ (s)</th>
<th>$T_{C,2}$ (s)</th>
<th>Drift Error (mV)</th>
<th>$T_{S,1}$ (s)</th>
<th>$T_{S,2}$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>Original(a)</td>
<td>5.97</td>
<td>5.52</td>
<td>21.6</td>
<td>24.91</td>
<td>16.04</td>
</tr>
<tr>
<td></td>
<td>Minimal(b)</td>
<td>N/A</td>
<td>N/A</td>
<td>6.2</td>
<td>13.17</td>
<td>1.41</td>
</tr>
<tr>
<td></td>
<td>Large Wire(c)</td>
<td>N/A</td>
<td>N/A</td>
<td>22.3</td>
<td>3.05</td>
<td>8.40</td>
</tr>
<tr>
<td></td>
<td>Protected Wire(d)</td>
<td>N/A</td>
<td>N/A</td>
<td>9.3</td>
<td>1.35</td>
<td>0</td>
</tr>
<tr>
<td>40</td>
<td>Original(a)</td>
<td>6.91</td>
<td>6.44</td>
<td>80.2</td>
<td>20.35</td>
<td>22.30</td>
</tr>
<tr>
<td></td>
<td>Minimal(b)</td>
<td>N/A</td>
<td>N/A</td>
<td>2.9</td>
<td>1.1301</td>
<td>7.45</td>
</tr>
<tr>
<td></td>
<td>Large Wire(c)</td>
<td>N/A</td>
<td>N/A</td>
<td>62.0</td>
<td>11.64</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Protected Wire(d)</td>
<td>N/A</td>
<td>N/A</td>
<td>29.1</td>
<td>7.04</td>
<td>0</td>
</tr>
<tr>
<td>50</td>
<td>Original(a)</td>
<td>5.42</td>
<td>6.43</td>
<td>272.8</td>
<td>15.72</td>
<td>13.50</td>
</tr>
<tr>
<td></td>
<td>Minimal(b)</td>
<td>N/A</td>
<td>N/A</td>
<td>18.7</td>
<td>1.83</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>Large Wire(c)</td>
<td>N/A</td>
<td>N/A</td>
<td>31.5</td>
<td>15.77</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Protected Wire(d)</td>
<td>N/A</td>
<td>N/A</td>
<td>17.0</td>
<td>2.00</td>
<td>0.34</td>
</tr>
</tbody>
</table>

From Table 3.2, a time constant of around 6 seconds appears to characterize the response of the original cantilever under all measured loads when fitted with a line-of-best-fit modeled after a first order system.

Settling time is also largest in the original cantilever design with certain signals reaching toward the end of the sampled data for that region. This implies that the settling times might be even larger than recorded and are constrained by the amount of time sampled. This is in contrast to the other design’s settling times which are near immediate with larger durations mostly attributable to "hiccups" in the data sets such as seen in Fig. 3.4b. In fact, some signals settle within the 2 percent region before reaching the point of maximum change. By comparing the settling time between all cantilevers in all three different loads, the table shows that even with the "hiccups" stretching the time for certain signals, the settling time of the original cantilever’s design is always among the highest if not the highest in each loading for both responses.

The most noticeable trait present is the response seen in the Original cantilever’s design. After the mass is applied or relieved, the immediate jump is followed by a slow transient response which lasts for 10's of seconds. This behavior, which initially prompted these tests, is unobserved in
any of the three new cantilever designs.

Further irregularities are noticeable in the baseline readings before the mass is applied and after the mass is removed. For the Original cantilever, the steady-state voltage output before application and after removal of the weight is noticeably different with increased weight seeming to coincide with these differences becoming larger. While this fact exists in small degrees for the other cantilever designs, the steady-state differences are far less drastic being on the order of 20mV error versus 200mV error.

The following four tables describe how both strain gauges’ resistance in the half-bridge responded to the applied weight. These values are taken after the measurements seen in Fig(s). 3.3 - 3.5 with Gauge 1 and 2 signifying a connection to the powered or grounded lines respectively. The other two fields are computed from measurements taken from the experiment. The first of these computed values is the effective strain experienced by the strain gauges based on the mechanical conditions present using Eq. 2.17. The thickness $t$ is given in Table 3.1 and discounts the affect of all epoxy-based layers. $L$ is the effective length measured from the loading hole of the cantilever to the center of the strain gauge taken to be 10.97mm in all designs other than the original. The other computed field estimates the gauge factor present in the mounted strain gauges through use of Eq. 2.19 where the expected value based off the companies datasheet is $140 \pm 10$.

For the Original cantilever design, while the mass applied maybe similar to the other cantilevers, the perpendicular force exerted is different due to the bend. Furthermore, while measurements are taken from the cantilever responsible for Sensor 2, the power and ground lines for bridges on the same strip of metal, i.e Sensor 1/Sensor 2, Sensor 3/Sensor 4, and Sensor 5/Sensor 6, are soldered together resulting in a parallel configuration with Sensor 1’s strain gauges. This explains the lower total resistance value for the Original cantilever design when compared to the other cantilever designs.
Table 3.3 shows the original cantilever design’s resistance response to the applied loads. An important point to note is the near constant value of the gauge connected to ground, which is the inactive gauge of the half-bridge placed for temperature compensation. Slight changes in resistance between loads are observed on the gauge connected to power, which is the active gauge of the half-bridge. The ⋆ denotes measurements where, after removing the applied mass, the unloaded cantilever’s resistances do not match previously recorded values when no load is applied. For the 40g measurement, the unloaded baseline reading after removal of the mass is 1.959kΩ while for the 100g measurement, the unloaded baseline reading after the removal of the mass is 1.958kΩ. The calculated gauge factor tends to be around 66 with changes from this value attributable to round off error, such as in the case with the 20g and 50g load. Furthermore, due to the change in baseline readings observed, the resistance value after extracting the weights are used in Eq. 2.19 instead of the fixed value recorded in the first row. This is done to follow the actual response more closely and results in more precise estimated gauge factors.

<table>
<thead>
<tr>
<th>Applied Mass(g)</th>
<th>Gauge 1(kΩ)</th>
<th>Gauge 2(kΩ)</th>
<th>Strain</th>
<th>Estimated G.F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/A</td>
<td>1.960</td>
<td>1.945</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>1.960</td>
<td>1.945</td>
<td>7.82e-6</td>
<td>0</td>
</tr>
<tr>
<td>40</td>
<td>1.961 ⋆</td>
<td>1.945</td>
<td>15.6e-6</td>
<td>65.4</td>
</tr>
<tr>
<td>50</td>
<td>1.962</td>
<td>1.945</td>
<td>19.6e-6</td>
<td>78.1</td>
</tr>
<tr>
<td>100</td>
<td>1.963 ⋆</td>
<td>1.945</td>
<td>39.1e-6</td>
<td>65.3</td>
</tr>
</tbody>
</table>

Table 3.3: Measured Change in Resistance in the Original Cantilever Design for Various Weights
The Minimal cantilever design resistance response is shown in Table 3.4. The active gauge is again connected to the powered line while the inactive gauge is connected to the grounded line. A consistent rate of change is observed in the active element of around +3Ω/20g. A rate of change is also observed in the inactive element of the half-bridge of around -1Ω/20g. Furthermore, the estimated gauge factor is precise at around 165. An exception to this exists when the 50g mass is applied to the cantilever. The most likely reason for this variation is round-off error. Since the rate of change appears persistent throughout the tests, a change in load from 40g to 50g is expected to produce a change of +1.5Ω. This will be approximated as +2Ω based on the precision of the instrument used to measure the resistances. Overestimating the change will appear as an increased gauge factor.

<table>
<thead>
<tr>
<th>Applied Mass (g)</th>
<th>Gauge 1 (kΩ)</th>
<th>Gauge 2 (kΩ)</th>
<th>Strain</th>
<th>Estimated G.F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/A</td>
<td>2.542</td>
<td>2.556</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>2.541k</td>
<td>2.559</td>
<td>7.06e-6</td>
<td>166.</td>
</tr>
<tr>
<td>40</td>
<td>2.540</td>
<td>2.562</td>
<td>14.1e-6</td>
<td>166.</td>
</tr>
<tr>
<td>50</td>
<td>2.539</td>
<td>2.563</td>
<td>17.7e-6</td>
<td>155.</td>
</tr>
<tr>
<td>100</td>
<td>2.538</td>
<td>2.570</td>
<td>35.3e-6</td>
<td>155.</td>
</tr>
</tbody>
</table>

Table 3.5: Measured Change in Resistance in the Large Wire Cantilever Design for Various Weights

The Large Wire cantilever design resistance response is shown in Table 3.5. The active gauge of the half-bridge is connected to ground rather than power which is reflected in the larger response to change occurring on the grounded sensor. The response for the active gauge consistently exhibits a +3Ω/20g rate of change ratio. The inactive gauge, while not exhibiting a consistent rate of change between loads, does tend downward. The estimated gauge factor also appears to dip at weights greater than 50g from 166 to 155.
The Protected Wire resistance response is exhibited in Table 3.6. The active gauge's rate of change is again consistent at $+3\Omega/20\text{g}$ while the inactive gauge's rate of change is consistent at $-1\Omega/20\text{g}$. Furthermore, the estimated gauge factor is precise with consistent estimates of around 166. Just as in the Minimal design’s response, the estimated gauge factor veers higher for the 50g response with the most likely culprit being round-off error.

From these results, it can be surmised that while the difference of properties between the epoxies used in the Original cantilever's designs and the new cantilever design may have some affect, the primary cause for the anomalous response exhibited by the Original cantilever’s design is the inclusion of a protected covering layer over the strain gauge’s active element. This layer, which is initially added for the safety of the fragile gauges, contributed a dampening effect to the system in which the strain gauge is situated in the center of a blob of gelatinous material with non-linear properties.

This is furthermore the cause of the long “warm-up” period when powering the platform and settling period after constructing the platform. For the former, the epoxy present over and under the gauge delays the amount of time it takes for the cantilever’s components to be heated to equilibrium. For the latter, the cantilever undergoes a significant amount of deformation for which the Epoxy needs to reorganize. This can be surmised by the fact that these aspects are not seen in any of the new cantilever designs.

Also, based on the change in trends of the estimated gauge factor observed in Table 3.5 versus those seen in Table 3.4 and 3.6, a property exists in the Large Wire design which appears to cause variations in the measurements above certain weights which does not exist in the designs using magnet wire. This lends credence to the theory that the larger 22-gauge wires can affect the

<table>
<thead>
<tr>
<th>Applied Mass(g)</th>
<th>Gauge 1($k\Omega$)</th>
<th>Gauge 2($k\Omega$)</th>
<th>Strain</th>
<th>Estimated G.F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/A</td>
<td>2.552</td>
<td>2.570</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>2.555</td>
<td>2.569</td>
<td>7.06e-6</td>
<td>166</td>
</tr>
<tr>
<td>40</td>
<td>2.558</td>
<td>2.568</td>
<td>14.1e-6</td>
<td>166</td>
</tr>
<tr>
<td>50</td>
<td>2.560</td>
<td>2.568</td>
<td>17.7e-6</td>
<td>176</td>
</tr>
<tr>
<td>100g</td>
<td>2.567</td>
<td>2.565k</td>
<td>35.3e-6</td>
<td>166</td>
</tr>
</tbody>
</table>

Table 3.6: Measured Change in Resistance in the Protected Cantilever Design for Various Weights
response of the cantilevers to a greater extent than the smaller magnet wire. This might be due
to the fact that all the wires were placed in tension at the beginning of the tests in order to reach
the breadboard holding the passive elements and amplifiers. When greater magnitudes of load are
applied, the bending deformation causes the more rigid 22-gauge wire to resist this deformation more
so than the thinner and more malleable magnet wires. As such, the magnet wire may be preferable
when connecting the cantilever to other electrical components.
Chapter 4

Calibration

This chapter covers the calibration of the platform. Sec. 4.1 explains the mathematical model used to transform the cantilever’s voltage outputs to the forces and torques in each axes present in the load. Sec. 4.2 goes over the procedure used to calibrate the platform and calculate a calibration matrix. Sec. 4.3 details how the calibration matrix responds to the data samples used to calculate the calibration matrix.

4.1 Calibration Mathematical Model

This section discusses the mathematical model behind calibrating the platform.

As stated in Chapter 2, the performance of the platform is determined by the mechanical geometry defined by the relation in Eq. 2.14. From Eq. 2.14, the matrix relating applied loads to the forces exerted on each leg $J_A$ is defined as:

$$J_A = J + \frac{k_0}{k_1} S_0 S_0^T J^{-T}$$

where $J$ is the combined screw representation of each leg, $S_0$ is the screw representation of the compliant columns, $k_0$ is the stiffness of the compliant column, and $k_1$ is the stiffness of each leg. As such, the platforms performance is dependent on the positions, directions, and physical attributes of the compliant columns and the legs. For the platform to perform well, the relations between these attributes and all constraints discussed in Chapter 2 must be maintained.
However, due to flaws in the platform, the stiffness matrix $J_A$ can not be used to directly transform the platform’s outputs into applied loads. These flaws stem from dimensional errors when fabricating the components and other factors present when manufacturing the platform. Thus, a new model must calculated in order for the platform to correctly measure forces and torques.

The model used in [4] to describe the transformation of the platform’s measured strain signals in each leg to the applied loads after calibration is defined as:

$$w_e = C \ast v$$  \hspace{1cm} (4.2)

where the $C$ is the calibration matrix used to convert the six cantilever voltage outputs $v$ into the forces and torques on each axes $w_e$.

As mentioned in Chapter 2, since the legs of the Stewart Platform must be linearly independent and twists must produce unique deformations in each leg, the calibration matrix $C$ must be invertible. Since a characteristic of an invertible matrix is that the null space is a zero-vector, the platform at rest must produce 0V outputs on each cantilever. In other words, when the platform is subjected to no applied loads $|w_e| = 0$, the voltage outputs on each leg must be 0V as well.

This presents an issue as the amplifiers resting output is 2.5V as set by the reference pin in Sec. 2.2. While the off-set is introduced so that the platform can measure voltages in a range of 0V to 5V rather than -2.5V to 2.5V, using the voltage outputs in this range would mean the platform will observe loads when at rest and only observe no load when the platform is subjected to a load large enough to de-tension all legs. Thus, to correct for this flaw in the model, the signals must be modified so that, while the platform is at rest, the signal from each cantilever is 0V. This is accomplished through the inclusion of the Sensor Bias blocks in Fig. 2.12 from Sec. 2.3. By subtracting the value of the signal at rest from the actual signal, the platform is able to measure positive voltages while recording these outputs using 0V as the baseline.

## 4.2 Calibration Procedure

This section details the procedures used to calibrate the platform using the code found in Appendix A.

To calculate the value of the the calibration matrix $C$, [4] uses a least squares approach
defined by the equation

\[ C = (WV^T)(VV^T)^{-1} \]  

(4.3)

where \( W \) is a \( 6 \times n \) matrix comprised of \( n \) known loads and \( V \) is a \( 6 \times n \) matrix comprised of the corresponding voltage output on each leg.

Since the calibration matrix \( C \) is invertible, both \( W \) and \( V \) must be full rank to avoid loss in dimensions. This requires that \( W \), and by extension \( V \), must be constructed with enough loads to span the basis of forces and torques in all axes. Thus, the minimal amount of data sets required to form a calibration matrix is \( n \geq 6 \) where at least one load in \( W \) is used to define forces and torques in each axes independently.

As the loads in \( W \) must be known, a few modifications are made to the platform’s top plate to aid in applying the loads. Four holes are drilled into the platform’s top plate in a radially-symmetric pattern with each hole about 2.9cm from the center of the top plate. Screws are inserted from below the top plate into each hole. These holes are used to fix the calibration blocks, detailed in Appendix B.4, such that the top plate resembles the image in Fig. 4.1. The placement of these screws will indicate the orientation of the coordinate system on the surface of the top plate. A thread of fishing line is used to create a loop used to brace against either the calibration block or the screw. The other end of the fishing line is also used to create a loop from which weights will be hung.
The procedures used to calibrate the platform are semi-automated. The calibration code and all functions the code calls can be read in Appendix A. The main function is the Calibration.m file in Appendix A.3. By using the Calibration.m file, the program begins a step-by-step process to calibrate the platform.

At the beginning of each calibration process, the Setup.m file is called. The Setup.m file may be viewed in Appendix A.1.

As discussed in Sec. 3.2, the platform undergoes a ”warm-up” period when power is first applied. To avoid tuning the trimming-potentiometers before the changes caused by the ”warm-up” period die off, Setup.m produces a real-time graph spanning the operational voltage range to observe when the ”warm-up” period is ending. During this time, all Sensor Bias values from Fig. 2.12 are set to 2.5V. This allows the trimming-potentiometer’s to be tuned by looking at the plot.

Once the the ”warm-up” period is finished and the bridges have been tuned, pressing the enter key will increase the resolution of the graph to allow for more precise tuning. This is the last time the program will expect for tuning to occur on the trimming-potentiometer’s. After this point, the program will always attempt to hide off-set errors by changing the Sensor Bias blocks in Fig. 2.12. Pressing enter again will prompt the program to continue through the procedures.

After initializing the variables used to hold the recorded loads and voltages as well as other variables used for bookkeeping purposes, the SampleCollection.m file is called. The SampleCollection.m file may be seen in Appendix A.4 and performs the function of choosing loads to calibrate with. After initializing some more constant values, the program will display a prompt for component, direction, and weight.

To ensure that the matrix of loads $W$ is full rank, the loads applied in calibrating the platform are composed either of axial forces, causing pure translation, or axial torques, causing pure rotation. The method of applying these loads differ between applying shear loads and applying normal loads.

Forces along the z-axis and the torques around the x-axis and y-axis are induced by normal loads. Normal loads are applied perpendicular to the plane of the top plate in either direction and require two weights to apply. If the angle between the top plate and load veers from $90^\circ$, coupling between forces and torques will be characterized in the calibration matrix. To mitigate the off-set from the perpendicular, the calibration blocks are used to apply the normal loads. To apply a normal load directed downwards, the weight is hung from the washer located in the calibration block. To
apply a normal load directed upwards, fishing line is used to connect the calibration block to the weight. A pulley located above the platform is used to redirect the force and reduce the amount of force lost to friction. To apply a force along the z-axis, two weights of similar mass are hung in the same direction on opposing calibration blocks. As the net torque caused by the opposing weights cancels out, the platform views this configuration as a pure force directed along the z-axis at twice the magnitude of the individual weights. To apply a torque around the x-axis or y-axis, two weights of similar mass are hung in opposing directions on opposing calibration blocks. To apply a torque around the x-axis, the two calibration blocks on the y-axis are used and vice-versa. As the net force caused by the opposing weights cancels out, the platform views this configuration as a couple moment where the torque is equal to the mass of one weight times the distance between the calibration blocks.

Forces along the x-axis and y-axis and the torques around the z-axis are induced by shear loads. Shear loads are applied parallel to the surface of the top plate, making sure contact is not made with the top plate, and require either one or two weights to apply. To apply shear loads, the fishing lines connected to the screws in the top plate are used. While attempts were made to use the calibration block for shear loads, the block is not sturdy enough to resist deforming from the torque caused by the weight in this position. To apply a force along the x-axis or y-axis, the fishing line connected to the screw on the desired axis is used to hang a single weight. To apply a torque around the z-axis, two weights are hung in opposing directions on opposing screws. As the net force of the two weights cancels out, the platform views this configuration as a couple moment. A pulley located away from the platform is used to redirect the force. The line should be kept parallel with the surface of the top plate while avoiding making contact with the platform.

When a weight is applied to either the fishing line or the washer of the calibration block, the weight will regularly oscillate when left free to hang. As the oscillation of the weight can be observed in the outputs of each cantilever, these oscillations have a detrimental effect on the performance of the calibration matrix. To remedy this problem, the weight is placed on the platform before entering the component, direction, and applied weights prompted for by the program. The reason for this will be discussed in a bit but this process allows measurements to be taken once the oscillations in the weight die down.

Once the loads component, direction, and applied weight are input into the program, the ResetBias.m file is called. The ResetBias.m file may be viewed in Appendix A.2. The purpose of

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this file is to re-bias the platform’s resting position. By taking a 5 second sample of the platform’s
current outputs when all Sensor Bias blocks are set to 0, the file can compute and average for each
leg’s output and uses these averages to revalue the Sensor Bias blocks. Resetting the Sensor Bias
blocks each time a new sample is recorded ensures that the voltage measured from each leg does
not violate the conditions of the model discussed in Sec. 4.1. Also, by applying the load before the
Sensor Bias blocks are reset and allowing the oscillations of the weight to dissipate, the platform is
biased to view the applied load as part of the resting condition. Removing the load after this will
cause the platform to view a load of the same magnitude but applied in the opposite direction. The
benefit of using this virtual load over applying an actual load is the lack of oscillations in the virtual
load.

Once the Sensor Bias blocks are reset, the computer will begin recording the platform’s
outputs. The recording can be ended by pressing the enter key at which point a plot of the recorded
data will be generated. A prompt will pop up asking if the data sample taken between the re-biasing
event and pressing the enter key should be saved. This allows for an easy means to throw-out
garbage data sets caused by accidents such as touching the platform during re-biasing phases. If
the data sample is saved, a second prompt will appear to confirm whether the data should be used
in calibrating a new calibration matrix or not. Selecting the data sample for use in calibrating a
 calibration matrix will prompt the program to proceed through the following steps. Not selecting
the data sample for use in calibrating a calibration matrix will still save the data but bypass the
next couple of steps.

If the data set is chosen for use in calculating a calibration matrix, the program will ask for
two time stamps from the generate plot created by the data set. The time stamps will select two
regions from the data sample for use in Eq. 4.3.

The first region will cover the data set from time $t_0$ at the start of the sampled data set
to the first time stamp provided. The voltage values of this region are averaged together to obtain
a baseline reading for each sensor before removing the load. The second region will begin at the
second time stamp provided and end 1 second later. This region signifies the slice of the data sample
taken after the load is removed which is deemed stable enough to use for calibrating the platform.
The average voltage values from the first region are subtracted from the 10,000 individual voltage
values from the second region with respect to the six cantilevers.

While the selection of the two time stamps are made on a case-by-case basis, there are some
conditions placed on choosing the time stamps. The two regions should occur as close to each other as allowable to avoid drift caused by the slow transient response discussed in Sec. 3.2. While another option for the second region is to take the steady-state response after applying the load, this option is rejected for two reasons. Since the suturing system needs to measure loads applied by the needle in real-time, the decision is made to use the instantaneous response rather than the steady-state response. Also, while the steady-state response is likely the true response, the duration of forces and torques applied by the needle is too small to reach this value.

The rest of the program in file SampleCollection.m places the results within the matrix of loads $W$ and the corresponding voltage outputs $E$. The program saves the the data sample and the attributes used for each prompt. The program then asks if another load is to be sampled. If not, then the function in SampleCollection.m ends and the program returns to the Calibration.m file.

After ending the program in SampleCollection.m, a new calibration matrix is calculated using the least-squares equation from Eq. 4.3 with the voltage outputs in $E$ and applied loads $W$. The resulting matrix is used to revalue the Calibration Matrix block in Fig. 2.12.

As a last step to ensure all the cantilever's outputs are still balanced, the Setup.m file is run one more time followed immediately by a call to ResetBias.m.

So long as at least one sample of each component is collected, the platform is calibrated for use in each axes. To ensure the effect of signal errors are reduced in the calibration matrix, multiple samples of each component in different directions is advised.

### 4.3 Calibrated Platform’s Response to the Calibrating Loads

This section discusses the outcome of the calibration matrix $C$ when applied to the data samples used to calculate the calibration matrix. The data samples are collected through the same process as described in Sec. 4.2 with the recorded data sets used after the completion of the Calibration.m program.

Applying the procedures discussed in Sec. 4.2, seventeen samples of applied loads where recorded over the course of two days. Grouped by day, six samples of each component were taken the first day while twelve samples of each component in both directions were taken the second day.
From these seventeen samples, the resulting calibration matrix is calculated as

\[
C = \begin{bmatrix}
0.210 & -0.347 & 0.317 & -0.242 & 0.482 & -0.544 \\
-0.456 & 0.448 & 0.432 & -0.463 & 0.037 & 0.045 \\
1.41 & 1.35 & 1.21 & 1.10 & 1.22 & 1.23 \\
-4.23 & -3.03 & -3.66 & -4.66 & 7.83 & 8.28 \\
7.36 & 7.51 & -8.55 & -7.22 & -0.483 & 1.43 \\
2.93 & -3.38 & 2.99 & -2.75 & -2.46 & 2.83 \\
\end{bmatrix}
\]  

From observing \(C\), the relationship between forces and torques applied to the platform and the strains observed on each leg is defined. For example, the third row of the matrix transforms the outputs on each leg into the force along the z-axis \(F_Z\). Since all the numbers on the third row are positive, if a normal force is applied in the negative direction then the strains on each leg will be reduced with positive normal forces increasing the strains on each leg. The direct relation between the normal force and the strains on each leg is expected from the platform’s geometry as a negative normal force will work against the tension in each leg while a positive normal force will work with the tension in each leg. The other rows validate similar expectation of the loads effect on each leg where the sign of each element in the row will signify whether the strain on that leg will increase or decrease when the corresponding force or torque is applied in the positive direction.

As pairs of legs on each cantilever connect at the modified banjo bolt joint, discussed in 2.1.1.2, the magnitude of change in each leg’s strain is expected to be equivalent. Also, if the modified banjo bolt joint is successful in breaking the distribution of tension throughout the segment of wire shared between pairs of legs, then the direction of change in each leg’s strain will be able to differ in some forces and torques while be equivalent in others in keeping with the condition of linearly independent legs. As the first and second columns are one such pair of legs, the example set by them confirms the previous two statements. In the first and second columns, which correspond to Sensor 1 and Sensor 2, the direction of each magnitude is seen to change independently on elements in the same row with the magnitude of these changes being similar. While differences are observed in the magnitude between elements, these differences are usually minor in the first three rows which correspond to the three-axis forces. Larger differences are observed in the magnitudes of change in pairs of legs in rows corresponding to the three-axis torques. The largest differences in magnitudes
in each pair seem to occur consistently within the rows corresponding to the shear torques $T_X$ and $T_Y$. Possible reasons for the increased divergence in magnitudes from the rows corresponding to the three-axis torques will be discussed later in Sec. 5.1.

Another interesting feature of the calibration matrix appears in the last two columns corresponding to Sensor 5 and Sensor 6. While the magnitude of elements in other columns on each row appear to be constrained to the same relative range, the elements of the Sensor 5/6 pair break this trend in many of the rows. For instance, while the elements in the first four columns on the row corresponding to $T_Y$ are valued around 7 to 8, the last two columns are appear constrained to 0.4 and 1.4. In another case, the first four columns in the row correspond to $T_X$ are valued around 3 to 4 while the values of the last two columns appear as 7 and 8. This outlier status appears in all loads except for the rows corresponding to the normal force $F_Z$ and normal torque $T_Z$.

While dissembling and reconstructing the platform can result in new calibration matrices, the trends discussed above appear in all of them. The effects of these trends will be discussed later in Sec. 5.1.

After calculating the calibration matrix $C$ from Eq. 4.4, the data sets used to calculate $C$ are applied to the calibration matrix in accordance with Eq. 4.2. While some of these data sets are discussed in this section, all the data is available in the graphs of Appendix D.1.
Figure 4.2: Positive X Calibration Sample
In Figure 4.2, subfigure 4.2a shows the six voltage outputs from the cantilevers over the time that a known load is applied to the platform. Subfigure 4.2b shows the corresponding forces calculated from the sensor values using the calibration matrix from Eq. 4.4. Subfigure 4.2c shows the corresponding torques calculated from the sensor values using the same calibration matrix from Eq. 4.4.

The vertical lines on the graph denote the two regions discussed in Sec. 4.2 from which the data is selected for use in Eq. 4.3 for calculating the calibration matrix. The first region spans from time $t_0$ at the start of the sampled data set to the time stamp of the first vertical line. The second region spans the one second interval between the second and third vertical lines.

As discussed in Sec. 4.2, the method of applying loads to the platform may need one or two weights based on the load to be applied. This is the reason for certain figures displaying only one fast transient response while most others display two fast transient responses. Since the method of adding and removing weights to the system when calibrating is done manually, manipulating two weights into the correct positions at the same time is difficult. An example of this may be seen in Fig. 4.3 in which the data set in Fig. 4.3a represents the behavior expected from utilizing a single weight while the data set in Fig. 4.3b represents the response expected from utilizing two weights of equivalent mass.
Figure 4.3: Comparison of Different Applications of Weights

(a) Applying loads to the platform with 1 weight
Load: $F_X = +0.981 \text{ N}$

(b) Applying loads to the platform with 2 weights
Load: $F_Z = +0.981 \text{ N}$
Chapter 5

Platform Performance

This chapter describes the platform’s performance to loads not used in calibrating the platform. Sec. 5.1 discusses the response of the platform to known loads that are similar to the loads applied when calibrating the platform taken a day after the platform was calibrated. Sec. 5.2 details the platform’s performance when subjected to a simulation of the suturing system using an external membrane holder.

5.1 Platform’s Response to Other Loads Over Time

This section details the performance of the platform’s response when subjected to known loads. The loads here are applied in the same manner as the loads applied in Chapter 4 with both the magnitude and direction of each load being known. Unlike in Chapter 4, the loads in this section are not used to compute a calibration matrix like in Sec. 4.3. Instead, the loads here are used to test the platform’s accuracy to loads not used in calibrating the platform. All loads in this section are also taken a day after the loads in Sec. 4.3 to test the effect of time on the platform’s performance.

Data samples taken a day after calibrating the platform are shown in Appendix D.2. These samples are collected through the same procedures seen in Sec. 4.2. The data samples collected are not used to create a new calibration matrix and must rely on the calibration performed on the platform the day before. The exclusion of the data samples from calibrating the platform is visually noted in the figures by an absence of the vertical lines used to signify the regions explained in Chapter 4.
As stated previously in Chapter 4, six samples, one for each force and torque, is the minimum amount of data required to calculate a calibration matrix. Therefore, the six data samples in Fig. 19 - 23 in Appendix D.2 are able to form a new calibration matrix. By using the older calibration matrix calculated the day before, the platform’s accuracy and precision to unknown loads is tested. Also, since the data samples are taken a day after the platform was calibrated, the platform’s resistance to change over time is also tested.

While the magnitudes of the estimated forces and torques differ slightly from the expected value, the response of the platform to both the loads obtained here and the loads used to calibrate the platform in Sec. 4.3 is roughly equivalent. Variations between the samples from each section can be attributable to inconsistent angles of applied load caused by "eyeing" the directions. The data samples taken here appear to be less smooth than the samples taken in Sec. 4.3, however, the source of this appears to be from the cantilever’s themselves. As the platform was active for a while before the the samples were taken, the erratic nature of the readings is likely due to the warmer strain gauges introducing noise.
Load: $F_Z = +1.96$ N

(a) 200g Positive Z Voltage

(b) 200g Positive Z Forces

(c) 200g Positive Z Torques

Figure 5.1: 200g Positive Z
Load: $F_Z = +0.392$ N

(a) 40g Positive Z Voltage

(b) 40g Positive Z Forces

(c) 40g Positive Z Torques

Figure 5.2: 40g Positive Z
Fig. 5.1 and Fig. 5.2 show the response of the platform under loads of magnitudes not calibrated for applied in the positive normal direction. While the data samples used in the calibration of the platform are taken with loads applied by 100g weights, a 200g weight and a 40g weight are used to apply a load along the positive normal axis in Fig. 5.1 and Fig. 5.2 respectively. As the loads exhibit magnitudes not calibrated for in the platform, the application of these loads tests the linearity of the platform’s outputs. In either case, considering the issues discussed in the Chapter 3 and the “warmed” strain gauges introducing more noise into the platform’s outputs, the platform’s response to varying loads of magnitude exhibit similar accuracy to loads both used in calibration and the loads discussed previously in the section. This implies the platform exhibits a linear relationship as loads of magnitude above and below those used for calibrating the platform exhibit similar responses.

While the platform is capable of measuring the expected load component correctly, an issue is seen in the coupling of this component with others components not present in the load. An example of this is shown in Fig. 5.3 which displays the platform’s response to a shear force of around 1N applied along the y-axis.
Figure 5.3: 100g Positive Y

Load: $F_Y = +0.981$ N

(a) 100g Positive Y Voltage

(b) 100g Positive Y Forces

(c) 100g Positive Y Torques
The response shown in Fig. 5.3 does measure the load accurately for an instant before slowly decreasing from the initial value until around the 20 second mark. The platform, however, measures other components of the load, most notable $F_Z$ and $T_Y$, which should not exist. As a similar trend is seen in the data sample shown in Fig. 10 in Appendix D.1 which is used to calibrate the platform to forces along the y-axis, the cause of the trend is likely a fault in the platform rather than a erroneous response to unknown loads. The most likely cause of this trend is the slow transient response discussed in Sec. 3.2.

As can be seen in subfigure 5.3a, while all the Sensors undergo some form of first-order response after the initial stimuli is applied, Sensor 2 in particular changes drastically after the initial response. In fact, the voltage value of Sensor 2 is nearly halved before steadying at the 20 second mark. As the time constant for the slow transient response from Sec. 3.2 is around 6 seconds, the observed trend on Sensor 2 along with the other Sensors is likely due to the dampening effect of the excess epoxy on the cantilevers. Considering the trends seen not only in the expected component $F_Y$ but also the erroneous components, the drastic change Sensor 2 undergoes is the likely cause of these components appearing in the measurements.

The effect of the slow transient response when calibrating the platform is also behind the appearance of the erroneous components in both the calibrated data set from Sec. 4.3 and the data set found here. As the the 1 second interval of the sample used to calibrate the platform needs to be taken soon after the initial response, as discussed in Sec. 4.2, the region used to calibrate the platform will include the slow transient responses effect on the cantilevers. In fact, the region will include the portion of the slow transient response where the voltage changes the most. Due to this fact, the measurement used to form the basis describing each load in the calibration matrix will be non-linearly reduced in magnitude from the actual value reached when the load is first applied. As the resulting basis for each component is insufficient to reach the outputs throughout the signal, other loads will be measured to account for the disparity.

As the new cantilever designs discussed in Sec. 3.2 eliminate the slow transient response, the solution for eliminating both the drift in the measurements and the appearance of erroneous load components is already known and left for future work.

Despite the coupling of pure forces and torques to erroneous components in the load, the platform is able to distinguish between the contributions of a force and a torque when both are present in a load. This ability is seen in the periods where one of two weights is removed from
the platform creating an off-center force. For example, when comparing Fig. 5.1b and 5.1c, a 100g weight is placed at approximately 2.9cm from the center of the platform for about one second before the second weight is added to produce a load of approximately 2N along the positive z-axis. This will cause a resulting torque of approximately 2.9Ncm measured from the y-axis. While the magnitude of the result is slightly overestimated, the expected relationship is seen with both a force of around 1N along the positive z-axis and a torque of approximately 3Ncm around the y-axis being recorded.

An estimated point of contact $r$ can be determined from the forces and torques in a load through the equation

$$ r = \frac{f \times m}{|f|} \quad (5.1) $$

where $f$ is the three dimensional force and $m$ is the three-axis torque, from [4]. As each of the six possible loading conditions discussed in Sec. 4.2 are applied at fixed points on the top plate, the actual points of contact on the top plate is known. Using Eq. 5.1 to estimate the contact points, the platform is able to compare the estimated positions of contact against the known location of these position. By doing so, a method of testing the platform’s ability to discern the relationship between forces and torques is implemented. If the platform is able to minimize the error between the estimated points of contact when compared to the known location of the contact points, then the platform is able to discern the parts of the load applied by pure translation from the parts of the load applied by pure rotation. This allows the platform to check that the relationship of forces and torques in loads of unknown magnitude and direction are being kept.

To test this method on known loads not used to calibrate the platform, data samples are taken from this section and used in Eq. 5.1. As Eq. 5.1 will produce estimated positions around the center of the device if applied a pure force or pure torque, only samples which display both a force and a torque are chosen. Furthermore, out of these selected samples, only the time interval a force is applied off-center on the top plate is used. The selected subsets of each sample are fed into Eq. 5.1 and averaged into single point per each sample. The average of each subset’s estimated point of contact is shown in Fig. 5.4. Since the loads used to calibrate the platform are applied on the top plate of the platform, all position estimates obtained from Eq. 5.1 are measured from the center of the top plate. The vertical origin is approximately level with the surface of the top plate.
Figure 5.4: Estimated Sampling Data Positions
The projected position of the estimated point of contact on the XY-plane for each load is given in Fig. 5.4a. Fig 5.4a is equivalent to an overhead view of the top plate with the estimated positions compared to the actual physical position of the applied load. The estimated distance of the point-of-contact from the surface of the top plate for each load is given in Fig. 5.4b. As can be seen in Fig. 5.4a, while there is some error in estimated positions of the point of contact, most of the points tend to group in the same general area. This shows the estimates tend to be precise and that certain positions on the top plate tend to be more accurate than others. Furthermore, Fig. 5.4b shows that while the vertical coordinate estimate is not as precise, the difference between the expected value and the estimation is mostly constrained to tenths of millimeters. A notable exception to this rule appears for loads applying torque around the vertical axis.

As such, while not a perfect means of validating responses to unknown loads, this method does allow the system to check the reliability of estimates to unknown loads if the point of contact is known. As the suturing simulator is already able to find the needles point of contact correctly, this will allow the platform to check the response for possible errors in estimation.

5.2 Platform’s Response to Membrane Test

While Sec. 5.1 focused on the application of known loads applied through the same procedures found in Chapter 4, this section discusses the performance of the platform when subjected to conditions similar to those found in the suturing system. A simulation of the suturing system is conducted on a membrane attached to the platform by a membrane holder. The membrane holder is fabricated to be fastened to the top plate of the platform through the use of three paper clips. This section discusses the platform’s response to the simulated test. The section goes on to detail the results of applying the data samples to Eq. 5.1 discussed in Sec. 5.1.

The figures in Appendix D.3 show the response of the platform when subjected to a similar scenario as seen in the suturing simulator.

As the current design of the top plate is unable to mount the membrane effectively, a membrane holder is developed to attach the membrane to the platform. The membrane holder may be seen in Appendix B.5 and is designed to be fabricated by 3D printing. The bottom of the membrane holder features three legs with extended feat. The dimensions of the legs allow the legs to be position over the tops of the compliant columns under the top plate. The extended feat allow
the membrane holder’s legs to be fastened to the top plate by large paper clips. The top of the membrane holder is designed to connect with the component currently used in the suturing system to hold the membrane. A small ring is glued in the center of the membrane holder forming a lip above the membrane holder. The lip is able to fit inside the top component holding the membrane to push the membrane up. This holds the membrane taut during the test. While this setup is a deviation from the original design methodology, the outcomes of the experiment are considered to be an appropriate approximation of how the platform would behave in the current suturing system.

The membrane is oriented as seen in Fig. 5.5. The radial lines on the membrane are equivalent to the position of hours on a clock with Position 0 occurring at 12 o’clock. The membrane is oriented such that Position 0 and Position 6 occur along the y-axis while Position 3 and Position 9 occur along the x-axis relative to the coordinate system of the platform.

Figure 5.5: Stitching Positions Defined
The test is conducted by a subject who goes through a full simulation of the suturing system’s test. The subject uses a needle with a small segment of thread attached to the end. To start the test, the subject begins a stitch on the radial line of Position 0 moving towards the center of the membrane. The subject proceeds to perform a stitch at each Position moving in a clock-wise direction around the membrane. A stitch is considered complete once both the needle and the thread are completely removed from the membrane. A data sample is taken for each Position stitched starting from before the stitch is applied up until the subject states that the thread is free from the membrane. To account for the drift discussed in Chapter 3, the platform’s software is re-biased between each stitch. The subject performs twelve stitches in total in the same order as the Position numbers.

Figures in Appendix D.3 are assigned designations based on where the initial penetration of the needle occurred with these designations corresponding to the locations present in Fig. 5.5.

All figures in Appendix D.3 display at least two transient responses. The first transient response is assumed to be the initial penetration, drive-through phase, and exiting penetration of the needle in the membrane while the following response is the pull-through phase of the stitch.
Fig. 5.6 displays the results of the stitch made to the membrane at Position 3 during the simulated test. As Position 3 occurs on the x-axis with the motion of the needle expected to travel along the x-axis, stitches made at Position 3 are expected to exhibit loads dominated by shear.
force along the x-axis and torque around the y-axis. As the load is dominated by the forces and

torques occurring along the x-axis and around the y-axis respectively in Fig. 5.6, this expectation

is validated. Similar assumptions may be made for each Position with the figures validating these

assumptions in most case.

Fig. 5.6 also shows the platform’s behavior when subjected to loads outside the platform’s

operational range. During the stitch at Position 3, Fig. 5.6a displays a 1.5 second time span where

the voltage output of Sensors 5 and 6 railed at -2.5V and 2.5V respectively. The platform interpreted

this event as being caused by a load with a shear force along the x-axis of around -4N. In fact, the

platform recorded an average force magnitude of 4.288N over this time span. The shear force along

the x-axis is nearly twice the magnitude of any previous load tested on the platform up until this

point.

The previous largest force never exceeded 2N in magnitude and was never applied off-center

on the top plate. The platform's response to 2N of force is expected to cause maximum changes

of 1.5V on any given Sensor. As the linearity of the platform is assumed from the tests conducted

in Sec. 5.1, 4N of force is expected to produce a maximum change of 3V on an given Sensor. As

this is outside the limits of the amplifier, the Sensor’s outputs would be expected to rail under these

conditions. This points to the amplifiers’ gain factors, currently set to 454, as being too large for

the application.

Similar instants of the user exceeding operational limits are observed from the stitches

performed at Positions 2, 5, and 11 which correspond to Fig(s). 26, 29, and 35 in Appendix D.3.

Some instances of the subject applying loads which exceed operational boundaries may be

partially due to the delayed responses discussed in Sec. 3.2. In order to keep the measurements

from the cantilevers centered around 0V, the platform is subjected to a re-biasing event after each

stitch where the Sensor Bias blocks seen in Fig. 2.12 are recalculated. As the purpose of the Sensor

Bias blocks is to hide the amplifier’s off-set error from the estimator while not fixing the actual

disparity of voltages on the amplifier’s inputs, the operational window of each Sensor will be shifted.

This will lead to increased limits in one direction at the cost of reducing limits in the other. This

results in exceeding the operational limits of the amplifier within the allowable range of loads. This

assumption is made based off cut-offs in signals being observed to occur outside the expected 2.5V

limit.

Following this test, the estimated position of the exit point for each stitch is found through
the utilization of Eq. 5.1 from Sec. 5.1. As estimated positions vary greatly over the course of each stitch due to off-set error discussed in Sec. 3.2, a portion of the sampled data is selected for use.

The time span chosen from the sampled data corresponds to the beginning of the needles exit from the underside of the membrane. This event is chosen as the focus for two reasons. The first reason is when the position is computed and plotted for the entire breadth of the sampled data, the region corresponding to the exiting phase of the needle is the most consistently stable in all Positions with large fluctuations in any dimension being absent. The second reason is that when compared to the estimated positions of other stable regions, such as the initial piercing of the needle through the membrane, the estimated position of the exiting phase appear to be more accurate. This is because the estimated positions of the exit points are closer to what is expected when taking the Position that the stitch is made into account. One assumption used to make this discrimination is the fact that since the membrane holder raises the plane of the membrane higher than the plane of the top plate, the estimated position along the vertical z-axis is expected to be both equivalent in height to the membrane holder and positive. As the entering height of the stitch is observed in most cases to be far smaller than the expected height and occasionally negative, which will indicate a stitch made into the solid top plate, this region in particular is not used.

The estimated positions calculated from the selected time spans are averaged together and displayed in Table 5.1.
<table>
<thead>
<tr>
<th>Position</th>
<th>X-Coordinate (cm)</th>
<th>Y-Coordinate (cm)</th>
<th>Z-Coordinate (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.3485</td>
<td>2.0258</td>
<td>2.7984</td>
</tr>
<tr>
<td>1</td>
<td>1.1050</td>
<td>1.3724</td>
<td>2.7274</td>
</tr>
<tr>
<td>2</td>
<td>2.1921</td>
<td>0.6869</td>
<td>3.0183</td>
</tr>
<tr>
<td>3</td>
<td>1.2333</td>
<td>0.2390</td>
<td>2.7299</td>
</tr>
<tr>
<td>4</td>
<td>1.3163</td>
<td>-1.3913</td>
<td>2.9162</td>
</tr>
<tr>
<td>5</td>
<td>-0.0281</td>
<td>-1.8368</td>
<td>3.2837</td>
</tr>
<tr>
<td>6</td>
<td>-0.2079</td>
<td>-2.3390</td>
<td>2.9733</td>
</tr>
<tr>
<td>7</td>
<td>-1.4214</td>
<td>-1.4060</td>
<td>2.7636</td>
</tr>
<tr>
<td>8</td>
<td>-1.4735</td>
<td>-0.6057</td>
<td>2.3865</td>
</tr>
<tr>
<td>9</td>
<td>-1.5839</td>
<td>0.9203</td>
<td>2.1241</td>
</tr>
<tr>
<td>10</td>
<td>-1.8579</td>
<td>1.3368</td>
<td>1.5249</td>
</tr>
<tr>
<td>11</td>
<td>-0.1225</td>
<td>1.7925</td>
<td>2.7846</td>
</tr>
</tbody>
</table>

Table 5.1: Estimated Stitch Exit Coordinates

As the calibration matrix is constructed from loads applied directly to the plane of the top plate, loads exerted on the membrane, with the membrane holder raising the plane of the membrane by approximately 3.1cm, will be offset from the surface. The difference between the estimated height above the surface of the top plate as compared to the expected height based on the dimensions of the membrane holder for each position is visualized in Fig. 5.7a.

From Fig. 5.7a, most every exit point falls short of this expected height but generally average around 2.8cm above the top plates surface. A noticeable exception to this trend is seen at Position 10 which exhibits an abnormal drop in height to around 1.5cm. This drop is conspicuous when compared to the large correction back to around normal levels seen right after in Position 11. A slight downwards trend is seen starting from Position 5 but the magnitude of the drop from Position 9 to Position 10 is not in keeping with this rate of change.

While Fig. 5.7a focuses on the z-dimensional estimations, Fig. 5.7b gives a visual representation of where the platform believes the needle exited the plane of the membrane from a top down view. Observed angular displacement from expected positions are likely to stem from three possible sources: membrane orientation, user error, and estimator error. The first error stems from
Figure 5.7: Position Estimates of Needle Exit Points on the Membrane
the fact that since the membrane holder is not directly connected to the top plate, the orientation of the membrane may not be in alignment with the orientation for which the platform is calibrated. The second error stems from the user not breaking through the membrane at the desired position. The third error is that, as seen in Fig. 5.4a, the estimator’s errors will affect the outcome of the estimated position. This results in observed errors such as Positions 0, 3, 6, and 9 occurring off axis. Just as in Sec. 4.3; however, a few crucial aspects known from the geometry are still present such as the near perpendicular intersection of the axial positions which approximately comes to 96.67°.

As stated at the end of Sec. 4.3, while the error’s in the estimated positions make them unsuitable for implementation at the moment, the trends observed in the placement of these positions are related to the unknown forces and torques exerted by the needle on the membrane. By observing these trends and how they relate to the expected exit positions, a means by which to test the platform’s ability to separate forces and torques exerted on the membrane is found.

For instance, the expected trend of each Positions placement in Fig. 5.7b is a clockwise circle with each point occurring on a hour hand. While a perfect circle is not formed, a clockwise trend is observed in nearly all Positions with the exception of Position 10. Furthermore, as stated previously, Positions 2, 3, 5 and 11 are all observed to exceed the operational limits of the transducer which may explain these estimates outlier status in the overall trend. The most noticeable break to the observed pattern is in the estimated exit point of Position 10. The fact that Position 10 also breaks the trend observed in Fig. 5.7a implies a fault with the design at this particular position. A fault in the design is further suspect as the trend observed in Fig. 5.7a appears to be robust against the errors known to occur in Positions 2, 3, 5, and 11.

One possible source of this design fault maybe seen in Fig. 5.5. Eight pairs of holes are seen to be situated around the membrane holder’s top and bottom components from which screws are used to fasten these components together. While utilizing only one of each pair is deemed sufficient, there is one pair that is unused due to the location occurring above one of the membrane holder’s legs. This leaves a slice of the membrane which is not as taut as the rest which will not only be more susceptible to bending deformation from external forces but also change the static parameters of the membrane around this region.

Furthermore, in order for the membrane to be pulled sufficiently taut, a lip is required to be fixed to the bottom component. This lip is used to push the membrane up through the hole in the top component which tightens the raised portion of the membrane. As the membrane holder did
not incorporate this structure at the time of manufacturing, a separate ring is printed and attached to the inner diameter of the bottom membrane holder with epoxy. Upon inspection of the joint, the inner ring is seen to have been pushed into misalignment in certain sections which will correspond to an unevenness in the membrane.

Finally, while the image in Fig. 5.5 is used to clarify the location of Positions on the membrane, this image is taken days after the suturing tests seen in Appendix D.3 and is not indicative of the orientation of the membrane holder during the test. In fact, there are three possible orientations that the membrane holder could have been placed in as the legs of the holder are designed to touch the top plate over the compliant columns. In one of these orientations, Position 10 will line up directly with the unfastened region.

Thus, while the accuracy and precision of the forces and torques applied to the membrane are unknown, calculating the estimated positions of exit points allows the platform to cross-check the estimated positions against the known positions. The platform is able to then use these trends to pinpoint problematic force and torque measurements in the data. With this method, the over-amplification of the platform and a faulty design in the membrane holder are observable from the position of contact estimation’s break from the overall trend.
Chapter 6

Conclusions

This thesis detailed the design, fabrication, and testing of a force - torque sensor for use in a suturing simulator. The suturing simulator is an ongoing project with the goal of creating a suture training system which provides real-time feedback to the user. The suturing simulator measures a variety of metrics including forces and torques applied by the needle on the stitching membrane. As the current sensor used to measure the loads applied by the needle is inhibiting the development of the suturing simulator, the purpose of the purposed sensor is to replace the current force - torque sensor.

The design of the sensor is based off the Stewart Platform manipulator configuration. The linear actuators present in the normal Stewart Platform are replaced by flexible metal wire connected to cantilevers used to measure strains in each leg. A group of compliant columns are used to keep the wires in tension and support the weight of the platform. The platform is designed to be fabricated by 3D printing were allowable.

The resulting platform is capable of measuring applied forces and torques for short spans of time. As the interior of the platform is clear of necessary hardware, modifications can be made to the top plate to mount the membrane directly to the force - torque sensor. The platform does not inhibit the access to the membrane from below to allow the suturing simulator’s camera an unobstructed view of the membrane’s underside to gather the simulator’s position based metrics. The platform does not inhibit the user from stitching on the membrane when mounted on the platform. By using flexible metal wire for the platform’s legs, the platform is less susceptible to non-linearity in the measurements caused by friction loss in joints. The flexible legs also allow the
platform to exhibit overload protection in certain directions by allowing the legs to go slack before damaging the cantilevers. The primary benefit of the platform to the suturing system is the ease by which the parts used to make the platform are inexpensively constructed and replaced.

After constructing and calibrating the platform, tests are conducted to observe the platform’s response to unknown loads. When subjected to forces and torques on each axes, the platform is able to measure the contribution of each component in the load. When the platform is subjected to tests simulating the suturing system, the platform is able to measure the forces and torques applied by the needle in any position on the membrane.

The platform must be either re-biased through software or re-tuned through the trimming-potentiometers periodically for the estimated forces and torques to remain near the neutral position while at rest. Due to faults present in the design of the cantilevers, the current platform’s voltage outputs tend to drift off value and exhibit a slow transient relationships between the applied loads and the measured strains in each leg. A coupling in measurements between forces and torques exhibits similar aspects to the non-linear response of the cantilevers. If the cantilevers are re-fabricated in the newer design, the platform’s performance will significantly improve.

6.0.1 Future Work

Currently, most of the electronics, i.e. amplifiers, filters, etc., are located on a breadboard positioned off the platform. While placing the electronics in this position allows the circuit to be modified more easily, the low voltage outputs from the cantilevers need to travel a longer distance to connect with the amplifiers. This introduces noise into the measurements. As such, future efforts should be made to place more circuitry on the platform to eliminate distance between the cantilevers and the amplifiers. One location suitable for mounting most of the electronics is on the mounting plate for each cantilever.

Furthermore, standard PLA plastic thread is used in the current platform for construction of the top and bottom plates and the struts for the compliant columns. While this material does not appear to cause issues in the performance of the platform, concerns with creep and deformation in the structure are present. Removing the cantilevers from the bottom plate reveals indentions left by the shim in the bottom plate. As such, the platforms printed components should be reprinted with stiffer plastic filament material or more filling internally to strengthen these components.

On the subject of reprinting components, the design of the platform’s plates should undergo
modifications. For instance, while the membrane holder fabricated to test the platform’s response to membrane was fairly successful, the ideal scenario for the platform is to directly measure loads applied to the membrane without the need for external mounts. This can be achieved by merging the design of the membrane holder with the top plate. The top plate can be printed in a donut-shape where the inner edge of the donut exhibits a raised lip. The top plate will then function as the membrane holder by applying the membrane directly to the top plate. With this modification, the top plate may measure the needle’s effect on the membrane while in direct contact with the membrane. Further modifications may be made to the bottom plate to incorporate the suturing system’s camera into the structure of the bottom plate.

Also, while many changes are made between the source material in [4] and the current platform, one potential issue of note is in the construction of the compliant columns. While the current platform’s compliant columns are rigidly locked to the top and bottom plates with epoxy, the sensor in [4] connects the column to the two plates with ball-and-socket universal joints. While the springs connecting the compliant columns to the top plate may act similarly to flexure joints, tests should be undertaken to see whether or not the addition of more compliant elements at the joints of the column may increase either accuracy or precision.

The current platform features a spring-to-cantilever stiffness ratio similar to [4]. As no tests were conducted to see if improved performance may be possible by increasing or decreasing these stiffness parameters, the stiffness ratio may not be optimized for the suturing system’s requirements. Thus, a future tests should be conducted on a modular platform design that allows for springs and cantilevers of varying stiffness’ to be tested on the same structure. The purpose of these tests would be to understand how the stiffness ratio between the compliant columns and the cantilevers influence both one another and the overall performance of the platform.
Appendices
Appendix A  Code

A.1 Setup.m

%% This is the first code that should be run.
%% It allows you two level of tuning the platforms bridges
%% with the first being mostly to see when the system has
%% warmed up and the second being used to fine tune it within
%% the range utilized to distinguish 2N of applied forces.
tg.stop;
scope1 = tg.getscope(1);
scope2 = tg.getscope(2);
scope3 = tg.getscope(3);
scope4 = tg.getscope(4);
scope1.YLimit = [-2.5,2.5];
scope1.NumSamples = 10000;
scope2.NumSamples = 10000;
scope4.NumSamples = 10000;
tg.setparam('Sensor 1 Bias','Value',2.5);
tg.setparam('Sensor 2 Bias','Value',2.5);
tg.setparam('Sensor 3 Bias','Value',2.5);
tg.setparam('Sensor 4 Bias','Value',2.5);
tg.setparam('Sensor 5 Bias','Value',2.5);
tg.setparam('Sensor 6 Bias','Value',2.5);
tg.start;
junk = input('Press enter when steady and largely zeroed');
scope1.YLimit = [-.5,.5];
junk = input('Press enter when steady and largely zeroed');
tg.stop;
scope1.NumSamples = 250000;
scope2.NumSamples = 250000;
A.2 ResetBias.m

% Modularized program for biasing all bridges to a neutral position
% Sets all sensor biases to 0, which would read as 2.5V, and record
% the output values for 5 seconds after which the biases are set to
% subtract the average output for each bridge thus automatically
% zeroing all strains
fprintf('Wait for bias reset\n');

tg.stop;
scope1 = tg.getscope(1);
scope2 = tg.getscope(2);
scope4 = tg.getscope(4);
scope1.NumSamples = 10000;
scope2.NumSamples = 10000;
scope4.NumSamples = 10000;
scope1.YLimit = [-2.5,2.5];
tg.setparam('Sensor 1 Bias','Value',0);
tg.setparam('Sensor 2 Bias','Value',0);
tg.setparam('Sensor 3 Bias','Value',0);
tg.setparam('Sensor 4 Bias','Value',0);
tg.setparam('Sensor 5 Bias','Value',0);
tg.setparam('Sensor 6 Bias','Value',0);
tg.StopTime = 5;
tg.start;
pause(5.5);
data = tg.OutputLog;
constants = mean(data(1000:length(data),1:6));
tg.setparam('Sensor 1 Bias','Value',constants(1));
tg.setparam('Sensor 2 Bias','Value',constants(2));
tg.setparam('Sensor 3 Bias','Value',constants(3));
tg.setparam('Sensor 4 Bias','Value',constants(4));
tg.setparam('Sensor 5 Bias','Value',constants(5));
tg.setparam('Sensor 6 Bias','Value',constants(6));

tg.StopTime = inf;

% if outside what would be the range observed for 2N, you need to
% spend more time tuning before running this program
% if sum(abs(constants - 2.5) > 0.5) ~= 0
%    error('You need to do some adjustments');
% end

scope1.NumSamples = 25000;
scope2.NumSamples = 25000;
scope4.NumSamples = 25000;
scope2.YLimit = [-2,2];
scope4.YLimit = [-7,7];

tg.start;

A.3 Calibrate.m

close all

% two step process in tuning the trim-pots to a reasonable region
Set up
% initial wrench and voltage values for ease of construction
% because the data is sampled in n x 6 matrices, W
W = zeros(1,6); % W^T
E = zeros(1,6); % V^T

% templates used to define what direction is currently being sampled
% for use in pure forces/couple moments
X = [1 0 0 0 0 0]';
Y = [0 1 0 0 0 0]';
Z = [0 0 1 0 0 0]';
TX = [0 0 0 1 0 0]';
TY = [0 0 0 0 1 0]';
TZ = [0 0 0 0 0 1]';

Sample_Collection;
tg.stop;

% method of paper
% W = W(2:size(W,1),:); % mass applied + direction
% E = E(2:size(E,1),:); % voltages
% C = W*E'/(E*E');
W = W(2:size(W,1),:);
E = E(2:size(E,1),:);
C = (E\W)';
tg.setparam('Calibration Matrix', 'Value', C);
save('C', 'C');
fprintf('Calbration Complete
');
Setup
ResetBias
A.4 SampleCollection.m

cont = 'Y';
reg = 10000; %Sample Frequency - Hz

field1 = 'data';
field2 = 'region';
field3 = 'wrench';
field4 = 'voltage';
field5 = 'component';
field6 = 'direction';
field7 = 'mass';
field8 = 'bias';

% use only with pure forces or couple moments

g = 9.81; % Acceleration due to Gravity - m/s^2

r = 29.63*(10^-1); % Radius of Contact Points - cm

while cont == 'Y'
    filenamea = 'Test_';
    comp = input('Choose Component: X Y Z TX TY TZ: ','s');
    dir = input('Choose Direction: [+/-]: ','s');
    weight = input('What is the weight in grams: '); % ResetBias
    fprintf('Place weights on platform
');
    junk = input('Press enter when done sampling','s');

    tg.stop;
    data = tg.OutputLog;
    tg.start;

end
figure(1)
clf
hold on

plot(data);
axis([0 length(data) -2.5 2.5])
legend('S1','S2','S3','S4','S5','S6');
hold off

awful = input('Is this input acceptable: [Y]/[N]: ','s');

if awful == 'Y'
    cd ..
    cd Filtered_Calibrations

    used = input('Used for Calibration: [Y]/[N]: ','s');
    if used == 'Y'
        filenamea = strcat('(C2)',filenamea);
        a1 = input('Give me a good end for resting: ');
        a2 = input('Give me a good start for active: ');

        E_new = data(a2:(a2+reg),:) - mean(data(1:a1,:));

        switch(comp)
        case 'X'
            if dir == '+'
                W_new = (ones(1,reg+1).*X*weight*g/1000)';
            elseif dir == '-'
                W_new = (ones(1,reg+1).*-X*weight*g/1000)';
            else

printf('Error')
end

case 'Y'
if dir == '+'
  \( W_{\text{new}} = (\text{ones}(1,\text{reg}+1) .* Y \times \text{weight} \times g / 1000)' \);
elseif dir == '-'
  \( W_{\text{new}} = (\text{ones}(1,\text{reg}+1) .* -Y \times \text{weight} \times g / 1000)' \);
else
  printf('Error')
end

case 'Z'
if dir == '+'
  \( W_{\text{new}} = (\text{ones}(1,\text{reg}+1) .* Z \times \text{weight} \times g / 1000)' \);
elseif dir == '-'
  \( W_{\text{new}} = (\text{ones}(1,\text{reg}+1) .* -Z \times \text{weight} \times g / 1000)' \);
else
  printf('Error')
end

case 'TX'
if dir == '+'
  \( W_{\text{new}} = (\text{ones}(1,\text{reg}+1) .* TX \times \text{weight} \times g / 1000 \times 2 \times r)' \);
elseif dir == '-'
  \( W_{\text{new}} = (\text{ones}(1,\text{reg}+1) .* -TX \times \text{weight} \times g / 1000 \times 2 \times r)' \);
else
  printf('Error')
end

case 'TY'
if dir == '+'
  \( W_{\text{new}} = (\text{ones}(1,\text{reg}+1) .* TY \times \text{weight} \times g / 1000 \times 2 \times r)' \);
elseif dir == '-'
  \( W_{\text{new}} = (\text{ones}(1,\text{reg}+1) .* -TY \times \text{weight} \times g / 1000 \times 2 \times r)' \);
else
    printf('Error')
end

case 'TZY'
    if dir == '+'
        W_new = (ones(1,reg+1).*TZ*weight*g/1000*2*r)';
    elseif dir == '-'
        W_new = (ones(1,reg+1).*-TZ*weight*g/1000*2*r)';
    else
        printf('Error')
    end

case 'TZX'
    if dir == '+'
        W_new = (ones(1,reg+1).*TZ*weight*g/1000*2*r)';
    elseif dir == '-'
        W_new = (ones(1,reg+1).*-TZ*weight*g/1000*2*r)';
    else
        printf('Error')
    end

case 'TZ'
    if dir == '+'
        W_new = (ones(1,reg+1).*TZ*weight*g/1000*2*r)';
    elseif dir == '-'
        W_new = (ones(1,reg+1).*-TZ*weight*g/1000*2*r)';
    else
        printf('Error')
    end
end

E = [E;E_new];
W = [W;W_new];
elseif used == 'N'
    a1 = 0;
    a2 = 0;
    E_new = '0';
    W_new = '0';
end

test = struct(field1,data,field2,[a1 a2],field3,W_new,field4,E_new,field5,comp,field6,dir,field7,weight,field8,constants);
filename = strcat(filenamea,num2str(weight),dir,num2str(comp),'.mat');
save(filename,'test');
end

cont = input('Continue: [Y]/[N]: ', 's');

cd ..
cd start
end
Appendix B  3D Printed Parts

B.1  Top

Figure 1: Top Plate

B.2  Bottom

Figure 2: Bottom Plate
B.3 Stilt

Figure 3: Stilt
B.4 Calibration Block

Figure 4: Calibration Block
B.5 Membrane Holder

Figure 5: Membrane Holder
Appendix C  Machined Parts

C.1 Cantilever

![Figure 6: Cantilever]

C.2 Block

![Figure 7: Block]
Appendix D   Graphs

D.1   Training Set

![Graphs showing V_out (V) vs. Load: \( F_X = 0.981 \) N for different sensors.

(a) Positive X Sample Used for Calibrations

![Graph showing Force (N) vs. Time (s) for calibrated system on positive X sample for Forces.

(b) Result of calibrated system on the positive X sample for Forces

![Graph showing Torque (Ncm) vs. Time (s) for calibrated system on positive X sample for Torque.

(c) Result of calibrated system on the positive X sample for Torque

Figure 8: Positive X Calibration Sample
Load: $F_X = -0.981$ N

Figure 9: Negative X Calibration Sample
Load: \( F_Y = +0.981 \text{ N} \)

(a) Positive Y Sample Used for Calibrations

(b) Result of calibrated system on the positive Y sample for Forces

(c) Result of calibrated system on the positive Y sample for Forces

Figure 10: Positive Y Calibration Sample
Load: $F_Z = +0.981$ N

(a) Positive Z Sample Used for Calibrations

(b) Result of calibrated system on the positive Z sample for Forces

(c) Result of calibrated system on the positive Z sample for Forces

Figure 11: Positive Z Calibration Sample
Load: $F_Z = -0.981 \text{ N}$

(a) Negative Z Sample Used for Calibrations

(b) Result of calibrated system on the negative Z sample for Forces

(c) Result of calibrated system on the negative Z sample for Forces

Figure 12: Negative Z Calibration Sample
Load: $T_X = +5.81 \text{ Ncm}$

Figure 13: Positive TX Calibration Sample
Load: $T_X = -5.81 \text{ Ncm}$

(a) Negative TX Sample Used for Calibrations

(b) Result of calibrated system on the negative TX sample for Forces

(c) Result of calibrated system on the negative TX sample for Torque

Figure 14: Negative TX Calibration Sample
Load: $T_Y = +5.81 \text{ Ncm}$

(a) Positive TY Sample Used for Calibrations

(b) Result of calibrated system on the positive TY sample for Forces

(c) Result of calibrated system on the positive TY sample for Forces

Figure 15: Positive TY Calibration Sample
Load: $T_Y = -5.81\ \text{Ncm}$

(a) Negative TY Sample Used for Calibrations

(b) Result of calibrated system on the negative TY sample for Forces

(c) Result of calibrated system on the negative TY sample for Forces

Figure 16: Negative TY Calibration Sample
Figure 17: Positive TZ Calibration Sample
Figure 18: Negative TZ Calibration Sample
D.2 Test Set

Figure 19: 100g Positive X

Load: $F_X = +0.981$ N

(a) 100g Positive X Voltage

(b) 100g Positive X Forces

(c) 100g Positive X Torques
Load: \( F_Z = +0.981 \text{ N} \)

(a) 100g Positive Z Voltage

(b) 100g Positive Z Forces

(c) 100g Positive Z Torques

Figure 20: 100g Positive Z
Load:  $T_X = -5.81 \text{ Ncm}$

(a) 100g Positive TX Voltage

(b) 100g Positive TX Forces

(c) 100g Positive TX Torques

Figure 21: 100g Positive TX
Figure 22: 100g Positive TY
Figure 23: 100g Positive TZ
D.3 Suturing Graphs

Figure 24: Position 0
Figure 25: Position 1
Figure 26: Position 2
Figure 27: Position 3
Figure 28: Position 4
Figure 29: Position 5
Figure 30: Position 6
Figure 31: Position 7
Figure 32: Position 8
Figure 33: Position 9
Figure 34: Position 10
Figure 35: Position 11
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