Design and Calibration of a 2-axis Haptic Force Feedback Joystick

by

Will Pritchett

Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

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Abstract

The development of multi-axis force feedback joysticks enables mechanically coupled systems to be recreated by electronically coupled systems. A study of haptic force feedback systems was performed. A four-arm joint mechanism was designed and developed to enable multi-axis haptic force feedback. The joint mechanism was manufactured and preliminary validation experiments were performed. It was found that the joint mechanism accurately transmits forces proportional to the current applied to each drive motor and that the joystick mechanism developed in this thesis can be further validated and developed for specific applications of haptic force feedback.

Thesis Supervisor: Ian W. Hunter
Tile: Hatsopoulos Professor of Mechanical Engineering

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Chapter 1

Introduction

The purpose of this thesis is to describe the design and validation of a 2-axis joystick that is capable of simultaneously receiving commands from and providing force feedback to a user.

1.1 Background

Similar devices have been developed for extremely high-cost, high-risk areas. They are used in fly-by-wire systems where the pilot's controls are connected to the aircraft control surfaces purely by electronic cables, instead of mechanical couplings [1]. To change the pitch of the aircraft, the pilot moves the joystick. When the pilot pulls back on joystick in the cockpit, the change in the joystick's angular position is measured and an electrical signal is transmitted to an onboard controller. This controller transmits the signal to the rear of the aircraft, where actuators move the elevator, the control surface that affects the pitch of the aircraft. The system is doing until the entire airplane has begun to move. The pilot also has no idea what forces are being exerted by the elevator. The actuators will exert the force necessary to move the elevator to the position determined by the input received from the position of the pilot's joystick, up to the physical limits of the motor or limits placed by the controller. While previous mechanical systems provided tactile feedback to the pilot, directly transmitting forces between the pilot and the elevator, this electronic system removes this tactile feedback [2].

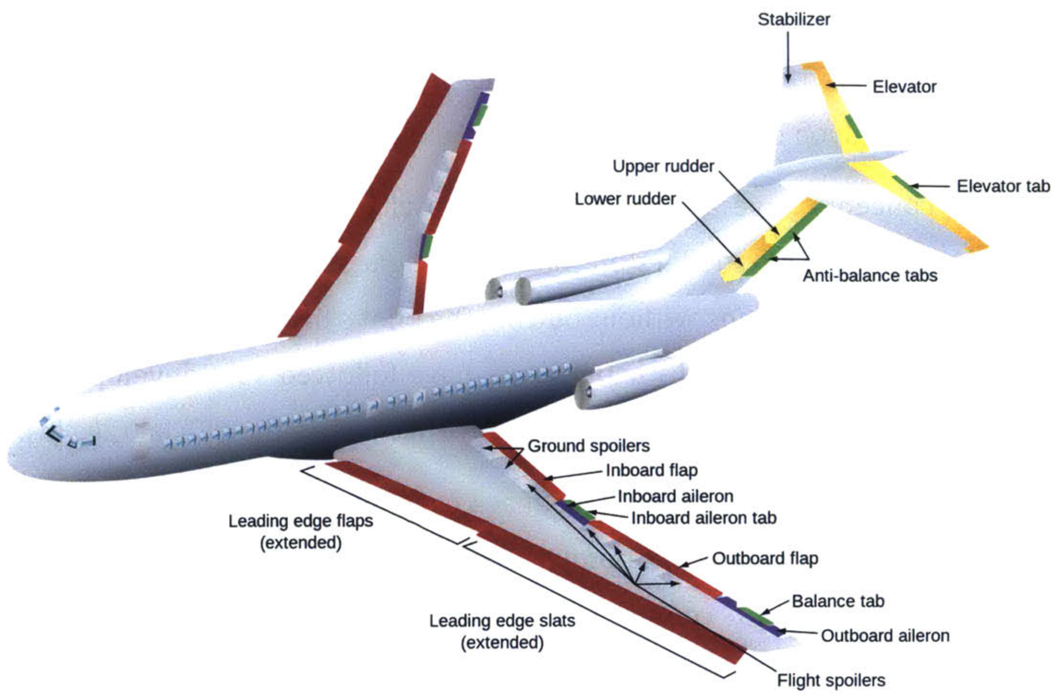

Figure 1-1: The pilot, from the front of the aircraft, controls many surfaces at the opposite extremities of the aircraft. While earlier aircraft utilized cables to mechanically connect the pilot to each actuator, modern aircraft use electrical signals to do the same, from [3].

Complex control systems have been implemented in many fly-by-wire aircraft to reintroduce this tactile feedback by measuring the forces applied by the actuators on the elevator and reproducing a proportional torque with motors attached to the pilot's joystick [1]. With accurate feedback controls, the feeling of a direct connection between the pilot's joystick and the elevator can be recreated and a clear weakness in fly-by-wire systems can be diminished. Actually, this weakness can become a strength now that the proportion of force feedback to the pilot can be modified in the onboard computer. Without the weight of mechanical linkages or the complexity of manufacturing mechanical force multipliers, a small force by the pilot can be easily tranlated into major forces applied on the elevator. Large resistive forces caused by air passing over the elevator can also be translated into small forces on the pilot's joystick, and pilots can dictate what proportion of that force should be applied to their individual joystick. They may want more or less force on the joystick for a given environmental force on the elevator.

Similar concepts have also been applied to virtual reality simulation set-ups. Airlines spend millions of dollars on individual flight simulators, allowing pilots to train in dangerous situations without putting the pilot's lives or expensive aircraft at risk. In recent years, high-end racing teams have followed suit, developing virtual reality simulators for their drivers to use as practice before the official race [4].

Both of these systems use force-feedback controllers to enhance the perception of virtual reality. The pilot's yoke moves forward and back in response to signals from the simulator's main computer. The steering wheel in the racing simulator responds to the virtual terrain, pulling left and right as the driver turns around each corner. While previous systems may have simply attached a spring to the controller, causing it to naturally return to a neutral postion, these modern electronic systems are controlled by electric motors receiving signals from a main computer. This allows the force-feedback to vary on more than just the driver's input.

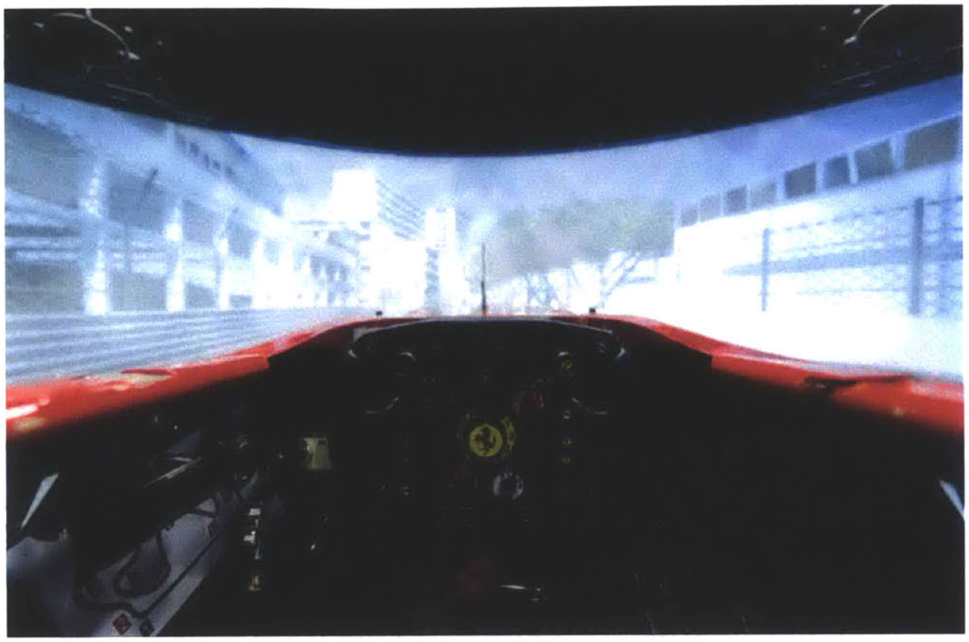

Figure 1-2: A racing simulator used by professional drivers to prepare for races, from [5]. Haptic feedback in the steering wheel, along with movements of the entire car body create the sensation of being in a virtual reality.

In these systems, changes in the virtual simulation affect the force-feedback response in the controller. The virtual road conditions and track geometry are translated into torques on the driver's steering wheel. Even the changes a technician makes to the suspension on the virtual racecar have a great affect on the stiffness of the controller during the simulation.

So far, the systems discussed have been very expensive and reserved for a limited number of individuals, namely professionals training to pilot the physical versions of a virtual reality. Similar, yet less sophisticated, technologies have also been implemented in video game controllers, enhancing the perception of virtual reality for a larger audience. For example, many force-feedback steering wheels, for use in racing video games, are available on the market. In comparison to their professional simulator counterparts, these controllers are relatively inexpensive, selling for only a couple hundred dollars [6].

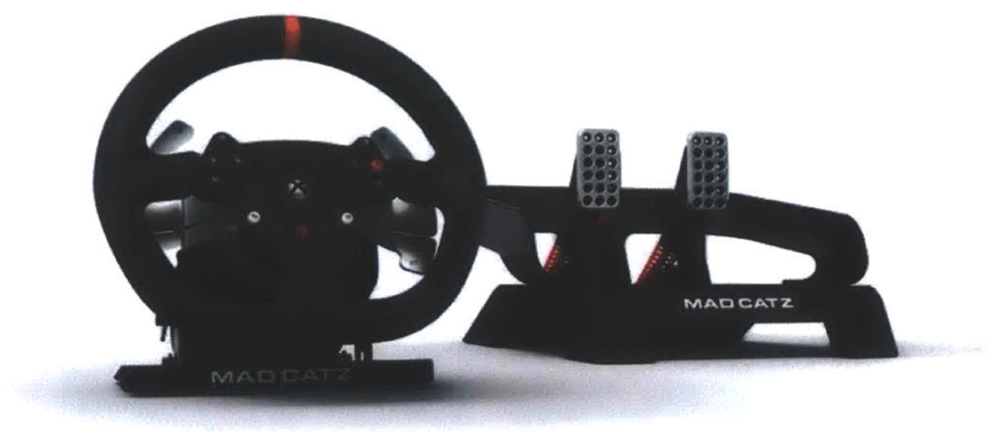

Figure 1-3: A popular force-feedback steering wheel for use with a household videogame console from [6]. Race enthusiasts and gamers alike can enjoy the haptic virtual reality sensation at a lower cost.

These steering wheels communicate the rotational position of the steering wheel to the video game console to control the car's position in the game. Meanwhile, the video game console returns signals to the steering wheel, activating an electric motor attached to the steering column. As the electric motor generates a torque, pulling the steering wheel left or right, drivers gain information about the virtual reality they are experiencing, just like the professional driver on a hundred thousand-dollar simulator. Even with their eyes closed, novice drivers may be able to feel a difference in the steering wheel when they are on pavement rather than a gravel surface. This feedback is a communication channel from the video game console to the driver, enhancing the perception of virtual reality.

Unfortunatly, the quality of the experience using one of these steering wheels designed for video games is far from reality [7]. Budget constraints and market demand often limit the quality of parts and design of the mass market products. The motors used are not capable of providing realistic feedback, lacking the frequency bandwidth to generate a true haptic sensation.

Previously, the demand for a general use haptic force-feedback controller has not been sufficient to outweigh the costs of development and implementation. However, as microprocessors continue to shrink in size and cost, automation continues to invade almost every industry and practice. More and more systems are being controlled through robotic systems, introducing electronic actuation and removing the user's tactile feedback [8]. Introducing haptic force-feedback control systems would reintroduce the connection and increase communication between the user and the environment, without bypassing the robotic system.

For example, robotic systems are increasingly being used to aid surgeons in complex surgical procedures. These systems provide great advantages to surgens, allowing them to make less and less invasive surgeries, and even filtering out small tremors from the surgeon's hand [9]. However, the introduction of the robotic system also creates a physical dissconnect between the surgeon and the patient. When a surgeon uses a scalpel, she is able to both apply a force onto the patient's tissue and feel a reactive force in her fingers, due to the principles described by Newton's third law. The exact same force exterted on the tissue by the scalpel is exerted on the scalpel by the tissue. In this case, the forces are transmitted directly through the scalpel. However, if that scalpel is replaced by a robotic tool, controlled by a conventional joystick without force-feedback, the surgeon may still be able to apply the same force onto the patient's tissue, but she cannot feel the reactive force in her fingers. Most often, she must rely on visual feedback to understand when the tool is in contact with the tissue or making an incision.

Developing a general use joystick that is capable of providing true haptic force feedback would not only enhance many robotic systems in use today, but it would open doors for many robotic systems that have not been implemented, due to the lack of control without force feedback.

1.2 Theory

In designing and developing this 2-axis joystick that is capable of providing haptic force feedback, four major principles were taken into account. First, the transfer of electricity into torques and forces. Second, the joining of rigid bodies to purposefully constrain specific degrees of freedom. Third, static response of a beam in bending, and fourth, a few of the physical requirements to provide haptic force feedback.

1.2.1 Torque Transfer

Torque (τ) is similar to force except torque deals with rotation about a point or an axis, while force acts in a specific direction and at a specific point. The simplest way to calculate a torque is to take the cross product of a Force (F) and the displacement (d) between the axis of rotation and the force point at which the force is being applied. In other words, multiply the displacement between the axis of rotation and the point at which the force is being applied, by the magnitude of the force acting perpendicular to that displacement,

$$\vec{\tau} = \vec{F} \times \vec{d}. \tag{1.1}$$

In static operation, the torque output of an electric motor is also proportional to the current (I) applied to the motor, with a proportionality constant (K_t),

$$\tau = K_t I. \tag{1.2}$$

When measuring the force exerted by an electric motor, Equations 1.1 and 1.2 can be combined. As seen in Equation 1.3, when the length of the lever-arm is constant, the force exerted perpendicular to the lever arm by an electric motor is proportional to the current applied to the motor. When the length increases, the force decreases linearly and when the length decreases, the force increases linearly,

$$F = \frac{\tau}{d} = \frac{K_t}{d} I. \tag{1.3}$$

1.2.2 Six Degrees of Freedom

Every rigid body has six degrees freedom. It can translate in three directions and it can rotate about 3 axes.

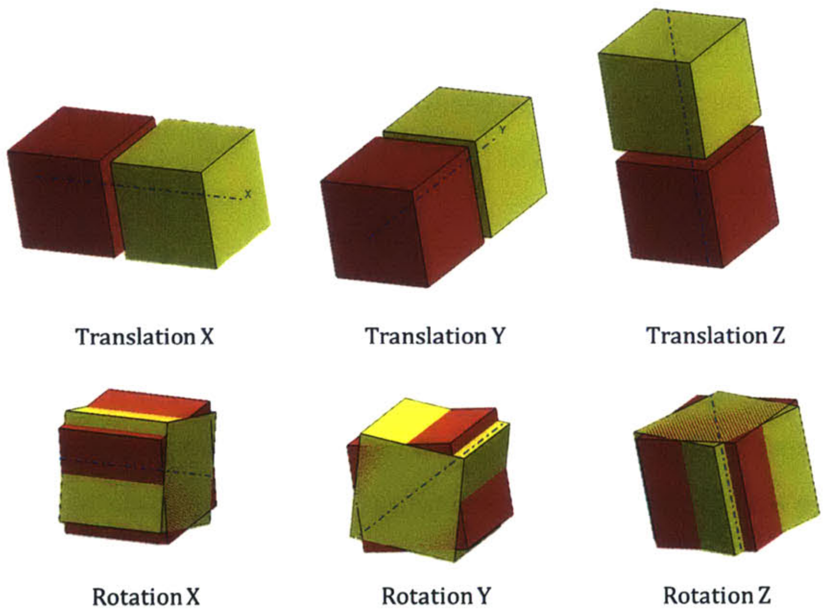

Figure 1-4: An unconstrained rigid body has six degrees of freedom. It can translate in three perpendicular directions and rotate about three perpendicular axes.

When joining two rigid bodies, they can be constrained with respect to one another in anywhere from one to six degrees of freedom. When two rigid bodies are constrained with respect to one another by a joint in all six degrees of freedom, the joint is completely fixed and the two rigid bodies can be treated as a single rigid body.

1.2.3 Beam Bending

Joint segments are often treated as rigid bodies in theoretical calculations. However, to create a physical segment that resembles a rigid body, the bending characteristics of each segment must be understood. It is important to not only ensure the segments do not yield and plastically deform, but also to minimize the defection of any point with respect to another on a single segment.

For every segment, the second moment of area can be calculated. To develop a guiding design principle, the arm was estimated to be a rectangular cantilevered beam. For a rectangular beam, the second moment of area *(I)* is dependent on the width *(b)* and the cube of the height *(h^3)* of the beam,

$$I = \frac{bh^3}{12} . \tag{1.4}$$

A cantilevered beam is a beam that is completely fixed at one end and completely unconstrained at the other. If a load is applied at the free end of a cantilevered beam, perpendicular to the longitudinal axis of the beam, the deflection *(d)* of the free end of the beam is dependent on the magnitude of the load *(P)*, the cube of the length *(L^3)* of the beam, the Young's modulus *(E)* of the beam material, and the second moment of area *(I)*,

$$d = \frac{PL^3}{3EI} . \tag{1.5}$$

1.2.4 Haptic Feedback

"The words 'haptics' and 'haptic' refer to everything concerning the sense of touch." [10] The study of haptic systems involves not only the tactile aspects of touch, but also the thermal- and pain-related aspects of touch. Without any sensory other sensory input, humans can perceive their environment as they touch various objects and sense the border of their existence. When you run your hand along a wooden table, it feels different than a stainless-steel countertop. That perception ability requires more than simply a tactile input. Our nervous system combines information from tactile sensors, thermal sensors, and nociceptors, which sense pain, to understand the edge of our self and the beginning of the world.

Humans are able to take in a wealth information about their environment through haptic channels, similar to how they understand their world through visual or auditory channels. This use of haptic channels to transmit information is being used in more and more electronic devices. For example, suppose a person receives a phone call on their cell phone. The recipient may be alerted that they are receiving a phone call through a visual channel when they see the incoming call on the phone's display. The recipient may be alerted by an auditory channel as the phone rings. Alternatively, the phone may be in the recipient's pocket, not making a sound, and simply vibrating against the recipient's leg. The vibration travels through a haptic channel to the recipient's brain, alerting them of the incoming call.

In this example, the haptic information being transferred is a sort of code. One vibration means a text, two vibrations means an email, and continuous vibrations means a phone call. However, electronic devices are also being developed to recreate more accurate physical sensations. Electronic devices that can recreate more realistic haptic perceptions of virtual objects, allow users to gain a more physical perception of virtual environments.

When a person grasps an object in their hand, they can feel the object and its response to their grasp through receptors in the tips of their fingers. Recreating that response in a user's hand, when using a robot to grasp an object in a very difficult task. To accurately represent that response, the wealth of information received by the tactile, thermal, and pain receptors must be recreated in the user's control device [11].

Another challenge in representing this response is due to the extremely high sensitivity of the human haptic perception. With their hands, humans can easily perceive vibrations with frequencies between 100 Hz and 1 kHz, with maximum sensitivity around 300 Hz. Therefore, when a person holds an object or moves his or her hand along a surface, they are able to perceive the surface texture, with deformations as small as 100 nm, as well as many high-frequency vibrations in the object [10,12]. To be able to recreate even just the tactile aspects of haptic perception, a device must be able to accurately recreate these deformations and vibrations in the bandwidth in which our fingers are able to perceive. Otherwise, when that information is lost through a robotic system, the haptic perception is incomplete.

Many systems have been implemented to recreate forces and torques and provide a tactile sense of either a virtual world or the world encountered by a robot. However, when the system is unable to provide tactile information in the 100 Hz to 1 kHz range, it is difficult for the human nervous system to have an accurate perception of the environment [10].

Chapter 2

Design

The joystick developed as a part of this thesis is able to rotate on two axes independently. Two limited angle torque motors independently apply torques on the joystick along each axis. Though it has not been implemented at this point, rotational position about each axis can be measured by coupling an encoder on the drive shaft of each motor.

The design of the joystick has 3 major characteristics that allow it to provide haptic force-feedback while simultaneously functioning as an input device. First, the joystick has two independent, perpendicular axes. The system is able to exert forces and measure rotational position on each axis independent of the other. Second, the joystick has a parallel construction. A parallel joint construction allows both motors to remain stationary, decreasing the mass that must be moved by the system. In a serial joint construction, one motor must move not only the joint, but also the mass of other motors in the joint. Decreasing the mass of the joint improves the performance of the system, especially at high frequencies. Third, the joystick system is coupled with two high-frequency, limited angle torque motors. The direct coupling improves the high frequency response as well.

A multi-step design process was used to better understand the key design principles for the system before the final joystick system was designed.

2.1 Single-axis Force Feedback Device

Before a 2-axis haptic force-feedback joystick could be a designed, a single-axis haptic force feedback joystick system was developed. The purpose of this system was to have two joysticks capable of following one another.

In this system, two single-axis joysticks are not mechanically coupled, but rather electronically coupled to one another. Each joystick is attached to a potentiometer on one end of the rotational axis and a DC motor on the opposing end. As the joystick is rotated, the output voltage from the potentiometer varies linearly with rotational position. A PSoC 4 microcontroller [13] is used to evaluate differences in output voltages from the two potentiometers. Treating these voltages as relative measurements of rotational position, the PSoC 4 microcontroller then outputs a current, proportional to the difference in potentiometer voltages, to the DC motor drivers. Each DC motor driver then outputs the amplified current proportional to the current supplied by the PSoC 4 microcontroller. So long as the torque output of the DC motors is proportional to the current supplied by each motor driver, the torque output on the joystick is proportional to the output determined by the PSoC 4 microcontroller. In the end, a greater difference between the rotational positions of the two joysticks causes a greater torque on each joystick. As the difference in position between the two joysticks diminishes, the torque applied on the joysticks also diminishes. Therefore, utilizing the functions of electronic components, the two mechanically uncoupled joysticks behave as if they were connected by a rotational spring with spring constant k,

$$\tau = k(\theta_1 - \theta_2)\,. \tag{2.1}$$

Similar to a mechanically coupled system, either joystick can be the master or the slave. When joystick 1 is moved 10 degrees, a corrective torque is applied to both joysticks until joystick 2 is once again in-line with joystick 1. When joystick 2 moves another 10 degrees, a corrective torque is similarly applied to both joysticks until joystick 1 is once again in-line with joystick 1. When an equal and opposite torque is applied to both joysticks, they move until the corrective torque generated by the virtual spring is equal and opposite the torque applied. The greater the torque applied to the two joysticks, the greater the separation as seen in Figure 2-1. Any time the forces are not balanced on the two joysticks, the joysticks will move relative to one another.

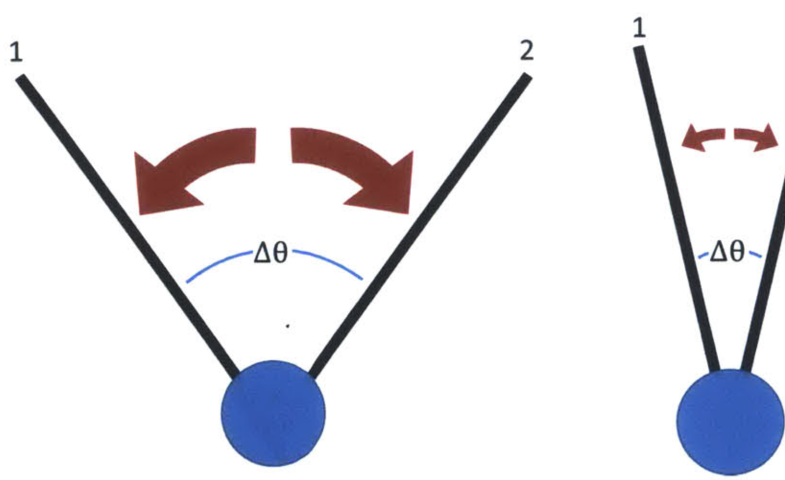

Figure 2-1: In this single-axis system, the two joysticks behave as if they were connected by a rotational spring. The two joysticks move relative to one another until the torques are balanced. The greater the torque applied, the larger the angular separation.

Newton's 3rd law is conserved between the two joysticks through the use of a virtual spring. Every action on joystick 1 causes an equal and opposite reaction on joystick 2 and vice versa.

The utility of this system is increased by the versatility of the microcontroller. If the two joysticks were coupled by a physical rotational spring, the spring constant would be fixed, unless a new rotational spring was installed.

However, by reprogramming the microcontroller, the spring constant can be easily varied. An added level of versatility can be introduced having two virtual spring constants, one for joystick 1 and another for joystick 2,

$$\tau_1 = k_1(\theta_1 - \theta_2)\ , \tag{2.2}$$

$$\tau_2 = k_2(\theta_1 - \theta_2)\ . \tag{2.3}$$

In this case, corrective torques, proportional to the difference in rotational position, will still be applied to each joystick and the two joysticks will track one another. However, greater torques will always be applied to one of the two joysticks.

In this case, as depicted in Figure 2-2, the two joysticks still behave as if they were connected by a rotational spring, however there is some power loss/gain between the two joysticks. If the spring constant for joystick 1 is greater than joystick 2, a weak torque on joystick 2 will be able to resist a large torque applied on joystick 1.

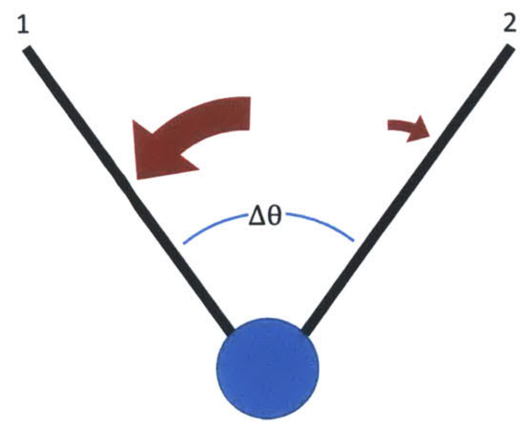

Figure 2-2: Due to the versatility of a microcontroller, the spring constants of the virtual spring can be easily manipulated. Different spring constants can even be applied to each joystick. In this case, the two joysticks act like they are coupled to one another with a spring, but a small torque on one joystick generates a large tore on the other, while maintaining a constant angular displacement.

The fixture mechanism for this system, as seen in Figure 2-3, was made out of 3 mm acrylic using a laser cutter. This allowed for digital designs, made with SolidWorks 2014 [14], to be rapidly implemented physically. Components that were readily available in the Bioinstrumentation laboratory were used, to reduce costs and function as a simple baseline. A 5-rotation potentiometer was used along with 29:1 DC gearmotors. The joystick was made of 2 pieces of 6 mm aluminum square rod. The rotational axis and handle pieces were connected in a T with an M4 stainless steel screw. One end of the rotational axis was turned down on the lathe and coupled to the potentiometer with a rigid coupling. On the other end, a hole was drilled into the rotational axis piece, and it was coupled to the motor with an M3 steel setscrew. By making the fixture with a laser cutter, the process of ensuring alignment among all the components along the rotational axis was simplified.

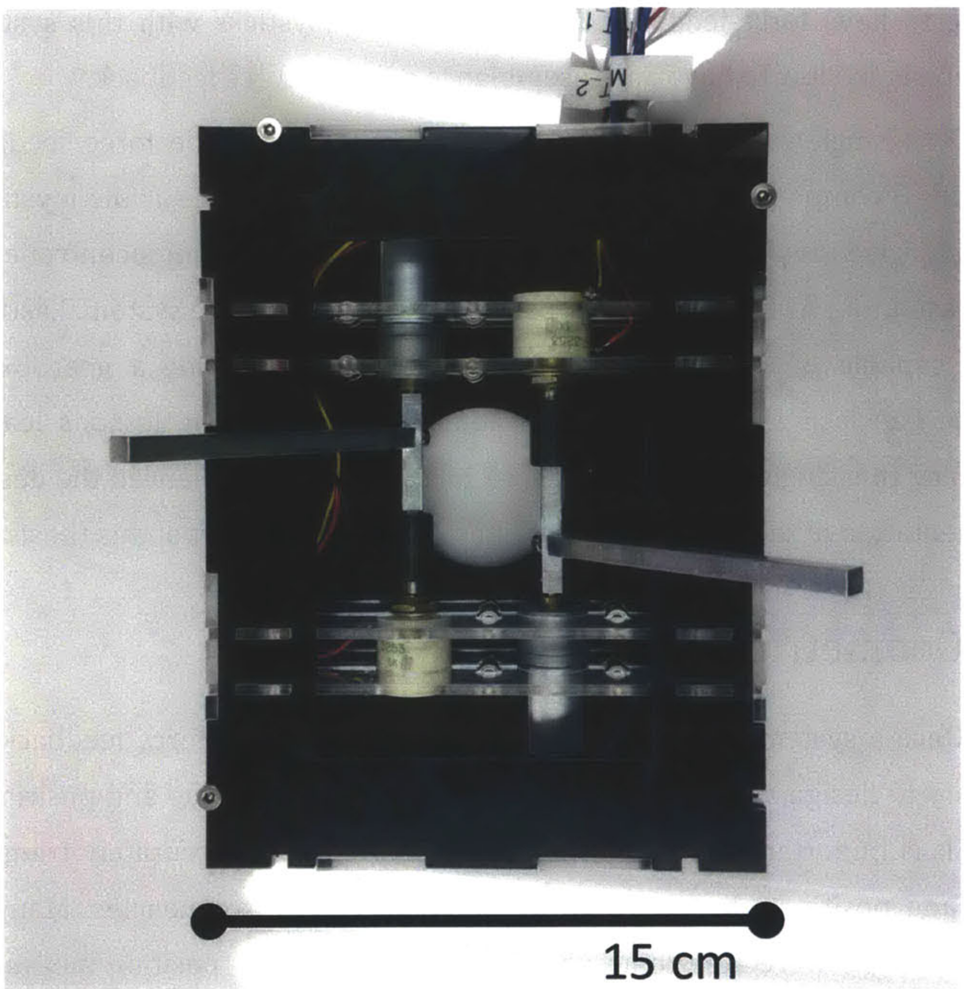

Figure 2-3: The single-axis force feedback model was made with an acrylic base and aluminum joysticks. Each joystick is coupled with a potentiometer and a gearmotor.

Due to these design considerations, this system was manufactured very quickly and precisely. However, a few poor decisions in component selection hindered the performance of the final product. Each joystick has a rotational position range of about +/- 30 degrees. Therefore, when a 5 V supply is used as a reference for the position sensors, the entire rotational position range of the joysticks translates to about a 167 mV range on the potentiometer. Therefore, given that the PSoC Analog-to-Digital Converter (ADC) is only an 8-bit ADC, it is only able to distinguish between 9 positions within the range the joysticks travel. Though it is possible to have force-feedback between the two joysticks with this system, the resolution is too low to have any resemblance of haptic force feedback.

This single axis system could be improved to provide force feedback by improving 3 components. A potentiometer with the same range as the joystick itself would improve the angular displacement resolution. Using a microcontroller with a larger resolution ADC would also improve the resolution of the system. Lastly, using motors capable of delivering high torques without requiring a gearbox would decrease backlash and improve the frequency response. The lessons learned in developing this single axis force feedback joystick system influenced the design and implementation of the 2-axis joystick system designed as a part of this thesis.

2.2 Geometric Study of a 2-axis Joint

Once a system had been designed to generate haptic force feedback, it was necessary to design a joint capable of easily transmitting torque and position along 2 axes. It is important that the joint is capable of not only accurately transmitting torque and position, but is capable of doing so at high frequencies. Many 2-axis joystick designs were able to accurately provide rotational position measurement, but were not able to easily transmit torque. Other designs were able to transmit torque, but lost resolution and high frequency response due to major backlash losses.

The design explored in this thesis is based on the principle of creating a structure where all of the joints fall on the face of a sphere. The system is made of a fixture, 5 rigid pivot joints, and 4 rigid arms. Each pivot joint has only a single degree of freedom, and because all five components connect at 2 joints, the entire system is a loop with 5 rigid bodies and 5 joints. At all times, the axes of rotation of each of the 5 pivot joints pass through a single point, the center of the sphere. In this design, the joystick would be attached to the joint farthest from both of the joints on the fixture. Therefore, it can be visualized as 5 joints along the surface of a sphere, where the rotational plane is always tangent to that sphere. In this design, the tip of the joystick is capable of moving along all the points in a large surface area of the sphere.

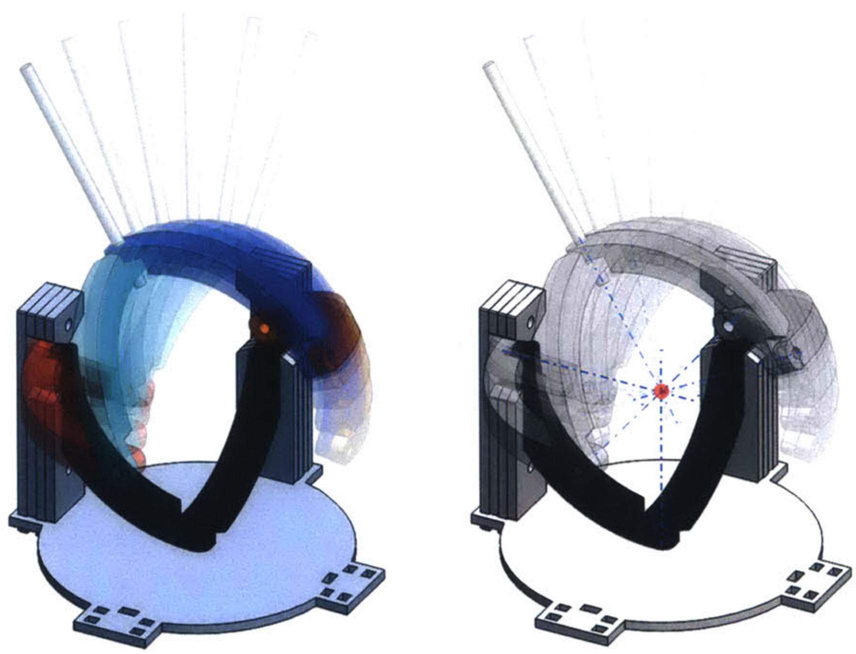

Figure 2-4: As the joystick moves, the axis of rotation of each of the five joints all cross at the same point. It can be imagined that all five joints travel along the surface of a sphere as the joystick changes position and all five axes intersect at the same point, the center of the sphere.

Multiple models were made to determine that there were no geometrical constraints in this joint design. First, a 3D model was made in SolidWorks, using a fixture and 5 pivot joints. Each rigid body is constrained in 5 degrees of freedom with it respect to its neighbor.

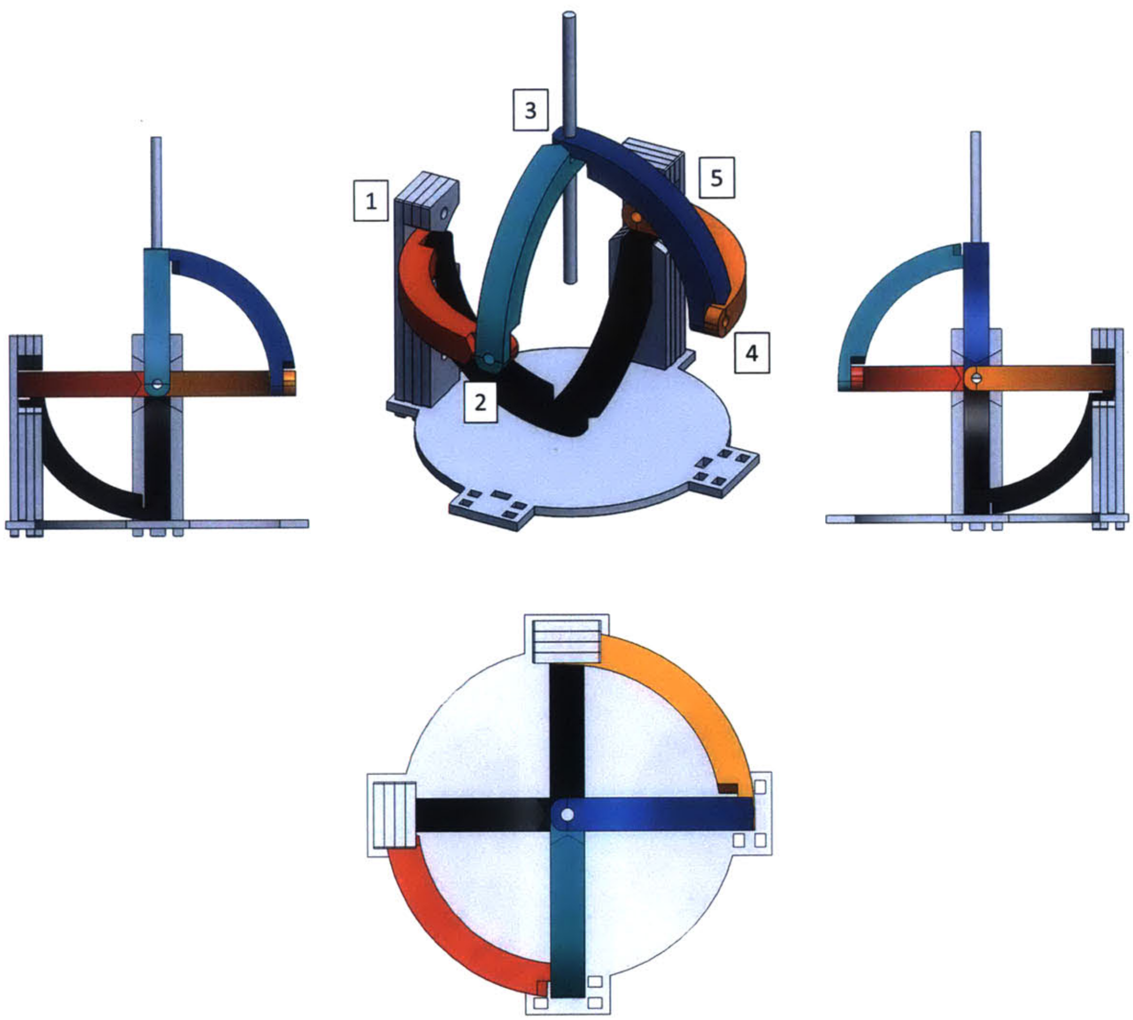

Figure 2-5: A 3D model was developed in SolidWorks to better understand the kinematics of the joint. Five segments (black, red, teal, blue, and orange) are joined by 5 single-axis pivot joints. This allows the joystick to rotate in two directions simultaneously.

The SolidWorks model proves the system works well so long as all the joints pointed to the center. When other variations were tested, with all joints along the face of a sphere and a few of the joints pointing in other directions, the system is constrained to a single axis. It is no longer capable of tracking along an area on the surface of the sphere, but only along a single line.

After exploring the 3D model on the computer, a physical model was made to better understand the function of the pivot joints. The fixture was laser cut out of 3 mm acrylic. The rigid arms were 3D printed with a Makerbot. M3 bolts with washers and lock nuts were used as the pivot joints. This physical model confirms the conclusions from the SolidWorks model, suggesting this joint design could be used to smoothly move a joystick along 2 axes.

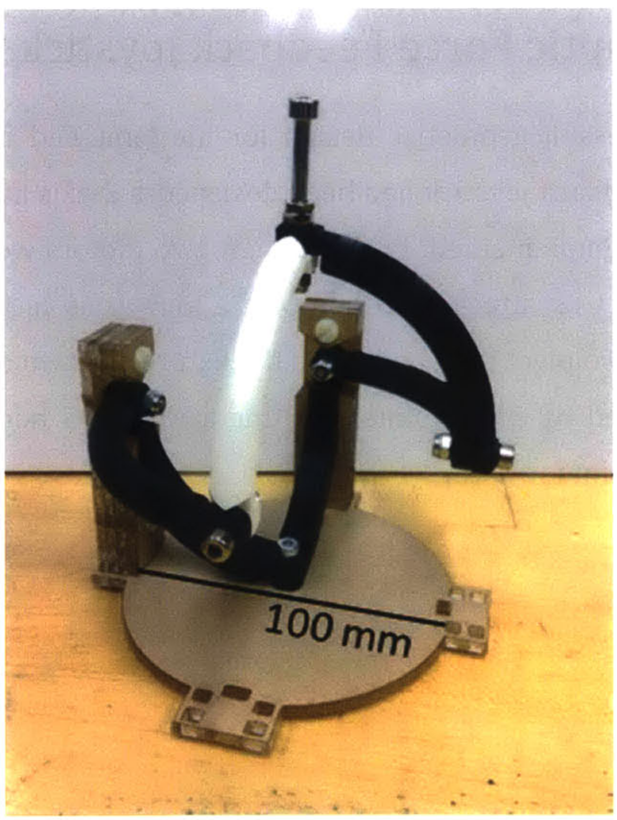

Figure 2-6: A physical model was made using a 3D printer and a laser cutter. Though the model was not actuated, it enabled an accurate geometric study to verify the theoretical designs.

The physical model also confirms that torque could be independently transmitted through each of the joints attached to the fixture. Figure 2-5 shows the 5 joints labeled numbers 1-5. Joints 1 and 5 are both joints between the fixture and a rigid arm, while the joystick runs through the center of joint 3. With the physical model, it was confirmed that torque can be applied through joint 1 and it is transmitted to joint 4 without causing any torque along joints 2 or 5 and vice versa. Therefore, a torque in joint 1 causes a torque in joint 4 and a force is transmitted to the joystick along one direction. In a completely independent manner, torques can be applied to joint 5, transmitted to joint 2, and a force is felt in the joystick along the perpendicular direction.

2.3 2-axis Haptic Force Feedback Joystick

After a successful geometric design for the joint had been verified and a single axis force-feedback joystick had been designed, a 2-axis haptic force-feedback joystick design was implemented. In this design, two motors were mounted on the fixture. Each motor was attached to one of the four arms in the geometric joint, therefore creating two pivot joints between the fixture and two of the arms. All four arms were connected by pivot joints, creating a ring of 5 bodies and five single degree of freedom joints.

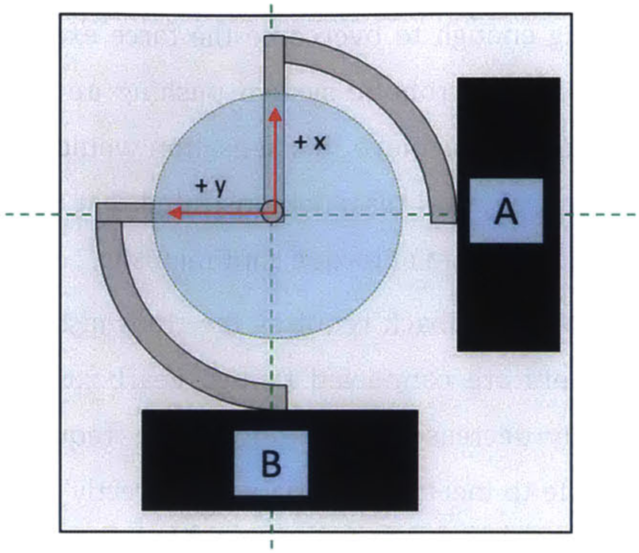

Figure 2-7: Schematic of an overhead view of the 2-axis joystick design. Motor A generates torque that correspond with force in the x direction. Motor B generates torque that corresponds with force in the y direction.

Moving from a theoretical model to a physical application, it was important to recognize the assumptions that had been made as a part of the theoretical model. For example, each of the 4 arms had been assumed to be a massless, rigid body. The greater the effective mass and the less rigid each arm was, the less accurate the torque transmission and position measurement would be.

Other assumptions had been made about each of the five pivot joints. First, it was assumed that five degrees of freedom would be constrained. Second, it was assumed that one rotational degree of freedom would be completely unconstrained. Third, it was assumed that each pivot joint would be perfectly aligned, with the unconstrained axis of rotation crossing perfectly through the center of the device. In the physical implementation, each joint had to be well aligned. It also had to constrain rotation in two directions, while minimizing friction and other losses in the third rotational degree of freedom.

When selecting motors to provide the force-feedback, a few design criteria were important. First, it was important that the motors were able to continuously generate a torque strong enough to overcome the force exerted by the user. This would be able to simulate the robotic system pushing up against a rigid object. Though the torque required to achieve this sensation would depend on the length and design of the joystick, physical tests demonstrated that the motors would need to be able to provide at least 1 N.m of torque continuously.

Second, haptic force feedback requires the transmission of torques at high frequencies. When motors are connected though gearboxes, backlash within the gearbox can significantly decrease resolution at high frequencies. Therefore, the motors needed to be able to meet all criteria when directly coupled to the joystick device, without the use of a gearbox.

Third, the motors needed to be able to provide a consistent torque across the entire range of the joystick. When a constant current was supplied to the motor, it needed to apply a constant torque to the joystick, even as the motor rotated though its range. After studying the uses of various joysticks, it was determined that a 60 degree range, from maximum to minimum extremities in each axis, was suitable for the design applications considered.

Certain motor characteristics were not considered crucial in this application, though they might be deemed crucial in other applications. Mass was not considered in the motor selection process, because in this application, the motors are stationary and mounted to rigid fixture. The overall mass of the motor has no effect on the performance of the joystick and even though the mass of the rotor itself has some effect on performance, it is minimal. In applications beyond a laboratory test bench scenario, the overall mass of the device may have a greater effect on performance. Similarly, physical volume was not considered in the motor selection process, though it may have a greater effect in other applications.

Efficiency was also not considered in the motor selection process. Laboratory power supplies were used to provide energy to the motors, so there was ample power available. However, in more mobile applications, where energy availability may be a constraint, it may be more important to recognize efficiency as a design criterion.

Given the important design criteria of continuous torque output, direct coupling capability, and a constant torque output over a significant range, a limited angle torque motor was used in this design. Limited angle torque motors are not designed to rotate continuously. Instead, they are optimized to provide an even consistent torque along a specific angular range. Many electric motors rely on significant gear reductions to convert many low-torque rotations into a few high-torque rotations. On the other hand, limited angle torque motors are designed to generate high torques when directly coupled to an output shaft. The limited angle torque motors used in this thesis, H2W Tech TMR-060-100-2V, run on a maximum of 50 V direct current [15]. They can continuously generate 1.8 N.m of torque and 5.3 N.m of torque at peak. The designed range for these motors is to have a consistent torque output over a 60-degree range. The motors are 47 mm thick and have a diameter of 114 mm.

As shown in Figure 2-8, an optical tabletop was used as the base for designing the 2-axis joystick system. Two right-angle extrusions of aluminum supported the motor shaft on both sides of the motor. On one side a ball-bearing was used while a nylon bushing was used on the other side. The stator of the motor was mounted to one of the right-angle extrusions with bolts, utilizing the mounting holes created by the manufacturer. The manufacturer had previously machined a 15.875 mm hole with a 4.76 mm square keyway into the rotor of the motor. Therefore, a matching 15.875 mm fully keyed 304 stainless steel shaft was used as the motor shaft. Using a ball-bearing/bushing on both sides of the motor constrains the motor shaft in four degrees of freedom. The motor shaft is free to rotate along its longitudinal axis as well as translate along its longitudinal axis, but cannot rotate or translate along the other two axes.

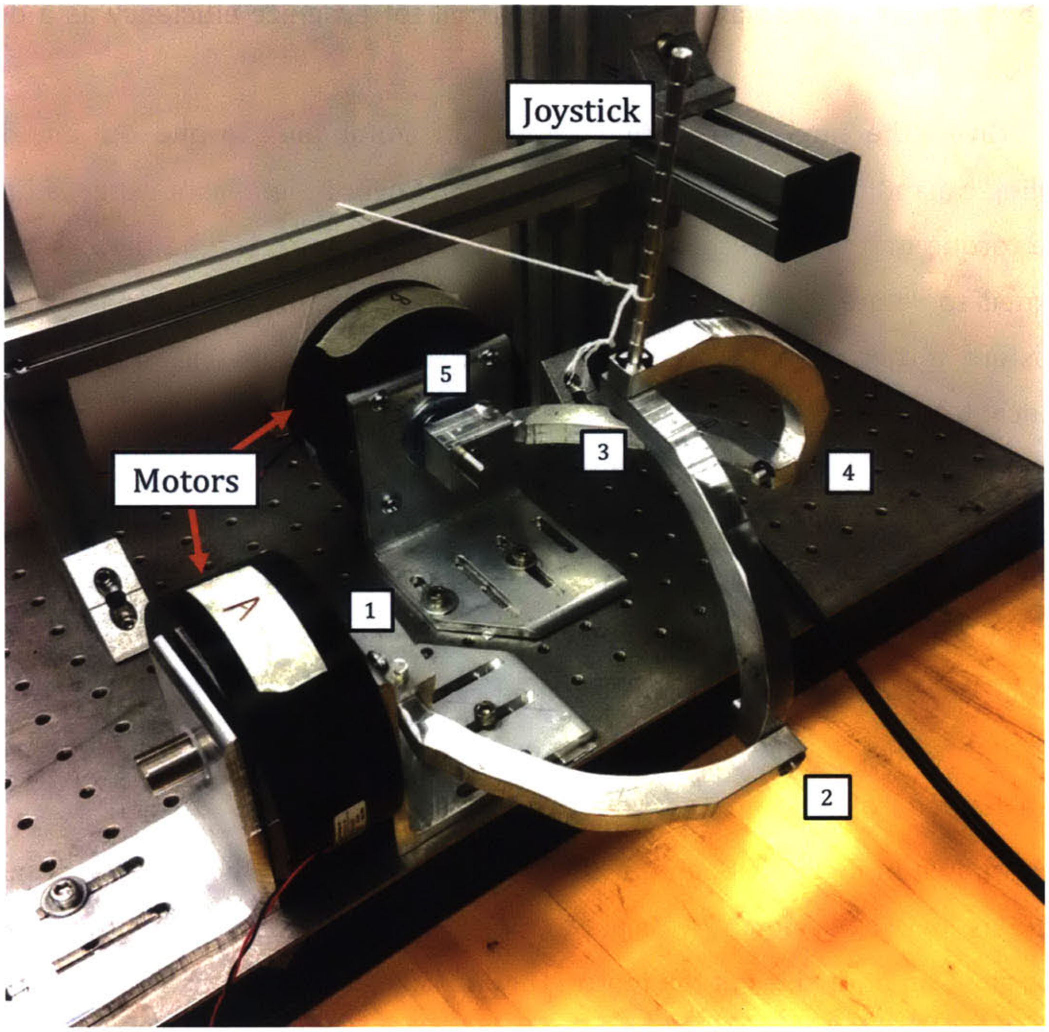

Figure 2-8: The 2-axis haptic force feedback joystick test apparatus. An optical table was used as a fixed base. Two limited angle torque are used to actuate the force feedback. Four arms are connected with by five pivot joints. A 25 V, 1 A power supply was used to apply constant direct current to the motors.

Placing a piece of key stock into the matching keyways on the motor shaft Sand motor rotor fixes the rotation of the two pieces relative to one another. Therefore, torque from the motor rotor is directly transferred to the motor shaft.

The arms were designed to be similar to massless rigid bodies. The curved shape transfers forces effectively from one joint to the other, while minimizing deflections, because the line of force is always passing through the neutral axis of the arm. The size of the arms in this thesis was expanded for ease in construction and to avoid geometric interference. However, the expanded size increases the mass of the arms, relative to the other components in the system. The longer arms are also more susceptible to deflections. If the size of the arms were to be decreased, the forces necessary to transfer a given torque would increase.

The arms were machined in such a way that the most critical dimensions and features were precisely machined first, allowing non-critical features to be machined afterwards. For example, the holes and mating surfaces for the joints were precisely machined on a mill, ensuring their alignment. Afterwards, the curved shape of the arms were cut with a band saw, because the shape of the arm was less critical than the mating features for each joint.

Each joint was designed to be a single-axis pivot joint. At each pivot joint, a 6 mm rod was press fit into an undersized hole in one arm. This press-fit constrained all six degrees of freedom between the rod and the arm. The other arm had a 6 mm ball bearing pressed into the arm. The rod was constrained in 2 degrees of translational freedom by the ball bearing. The ball bearing was 3 mm thick. Therefore, it also constrained two degrees of rotational freedom, however, a second ball bearing press fit on the other side of the arm would have more effectively constrained those rotational degrees of freedom. After inserting the rod into the ball bearing, an E-clip was pressed onto the rod, constraining the third translational degree of freedom. Therefore, the only unconstrained degree of freedom was the rotational degree of freedom about which the joint pivoted.

The electric motors also functioned as single-axis pivot joints. The motor shaft was coupled to the motor rotor with a keyway, and constrained by a ball bearing and a nylon bushing. One of the arms of the joystick system was then constrained in all six degrees of freedom with the motor shaft. A 15.875 mm hole was cut into the arm along with a 4.76 mm keyway, similar to the motor rotor. Using another key, the rotation of the motor shaft was fixed to the rotation of the arm. Therefore, once the arm was fixed in all six degrees of freedom to the motor shaft and motor rotor, the joint between the motor stator and motor rotor functioned as a single-axis pivot joint.

The final pivot joint was the joint farthest from both electric motors, where the joystick connected to the entire system. Similar to the other pivot joints, a 6 mm rod rotated inside a ball bearing. However, the 6 mm rod was extended 100 mm, creating a joystick. Also, the 6 mm rod was not press-fit into either of the arms. Instead a ball bearing was press-fit into both arms and an E-clip was used on both sides. This allowed the joystick to rotate freely.

Chapter 3

Calibration

The purpose of the validation experiment was to find the relationship between the current applied to each motor and the force required to resist the joystick along each corresponding axis.

3.1 Methodology

An Extech Instruments 475044 digital force gauge [16] was used to measure forces required to keep the joystick stationary. Currents, ranging from 0.4-0.8 A in both directions, were applied to each motor. As shown in Figure 3-1, the force was measured perpendicular to the axis of rotation.

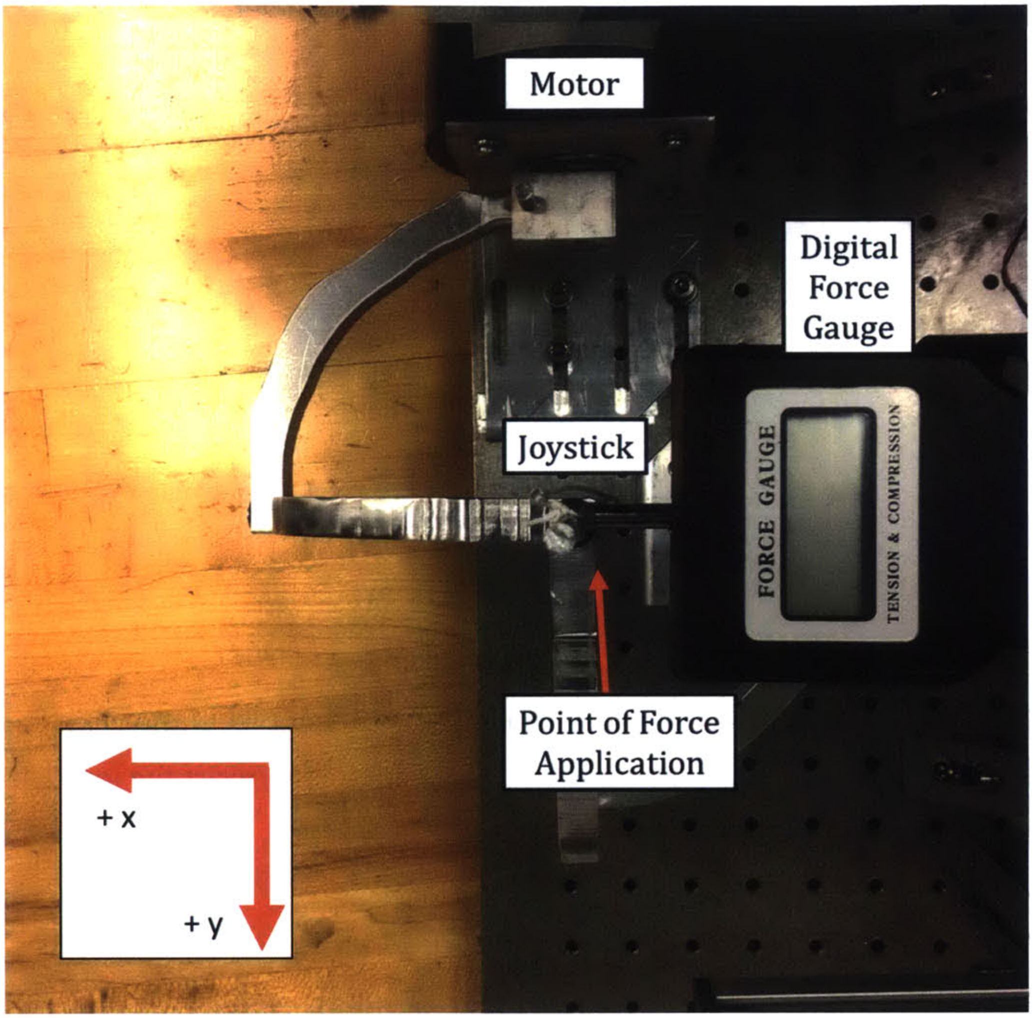

Figure 3-1: The test set-up to measure the force required to resist the torque exerted by each motor at various current levels. The digital force gauge was used to measure a compressive force in one direction and a tensile force in the other.

Even though the current was applied in both directions, the force gauge was kept in the same position. Therefore, a compressive force was measured for half the measurements, while a tensile force was measured when the direction of current flow was reversed. The force was always measured 140 mm away of the axis of rotation to keep a constant lever-arm.

3.2 Results

In total, 20 force measurements were made in four set-ups at five current levels in each set-up. Within each set-up, the force increased linearly, as shown in figure 3-2. When linear fits are applied to the data from each set-up, the R^2 values range from 0.982 to 0.999.

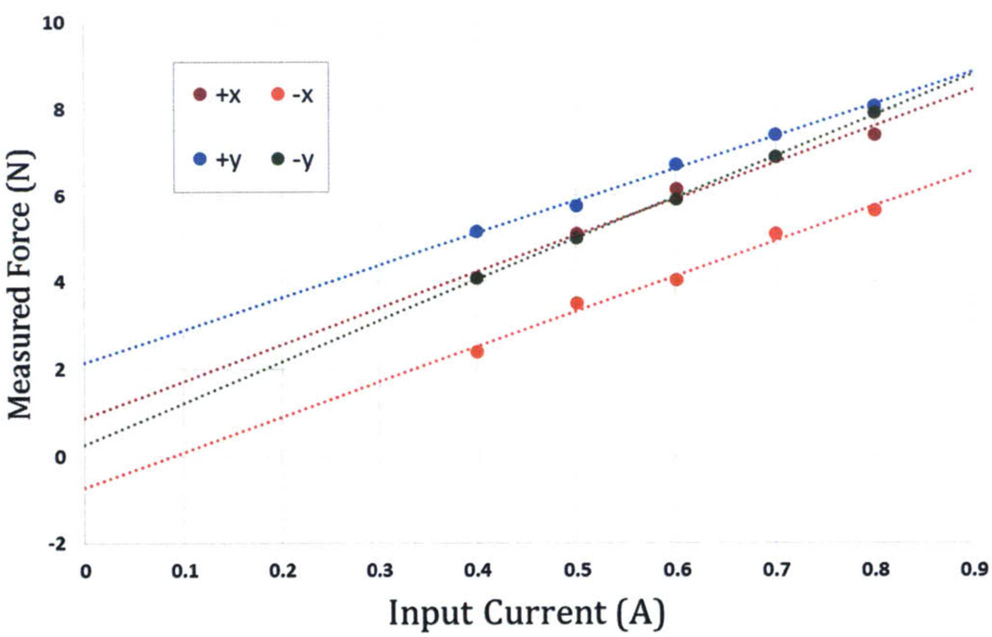

Figure 3-2: Forces exerted by the joystick were measured in all four directions at five different current levels. In each direction, the forces increased linearly with R^2 values ranging from 0.982 to 0.999.

Because the force measurements were always measured 140 mm away from the axis of rotation, the torque applied by the force gauge can be represented as a torque about the axis of rotation. The torque output from each motor could also be calculated using motor characteristics provided by the manufacturer.

For a more in-depth analysis of the device's response, each motor was studied separately. As shown in Figure 3-3, the torque curves for the torque measured in the positive and negative x directions were both linear. The linear fit applied to the positive x direction has a slope of 1.18±0.17 N.m/A and an intercept of 0.12±0.11 N.m on the vertical axis. The linear fit applied to the negative x direction had a slope of 1.13±0.14 N.m/A and an intercept of -0.100±0.019 N.m on the vertical axis. In comparison, the linear fit of the torque output by the motor, according to the manufacturer's specifications, has a slope of 1.095 N.m/A and crosses through the origin.

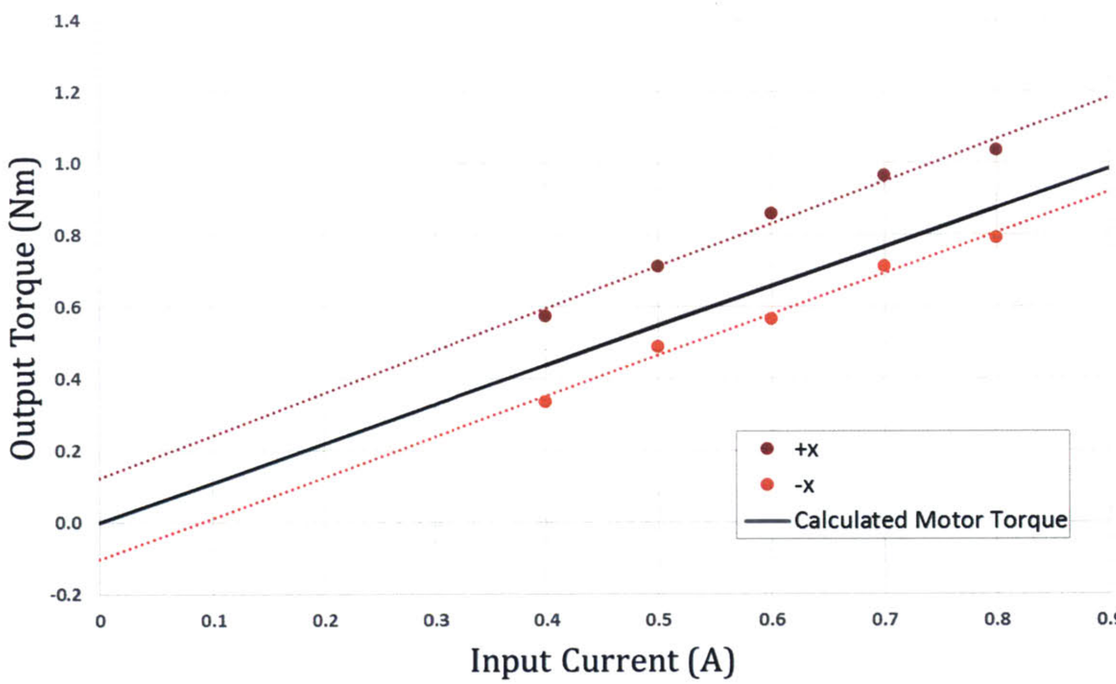

Figure 3-3: The torque exerted by the joystick was calculated by multiplying the measured force by the 140 mm lever-arm. The forces in the positive x direction were above the expected motor torque and the forces in the negative x direction were below the expected motor torque. This discrepancy may be caused by gravitational effects on the arms of the device.

On average, the torque measured in the positive x direction was 0.173±0.025 N.m larger than the expected torque given the manufacturer's specifications and in the negative x direction it was 0.077±0.019 N.m below the expected torque.

The slope of the torque output suggested by the manufacturer fits within the 95% confidence intervals of slope of the torque output by the device in both the positive and negative directions. This confirms that the device is accurately transferring torque from the electric motor to the joystick.

However, the intercept of the torque output suggested by the manufacturer does not fit within the 95% confidence interval of the intercept of the device output in either direction, which suggests there may be an external torque that is constant and not dependent on the input variable, the motor current.

Utilizing a 3D SolidWorks model of the two of the arms in the device, as shown in Figure 3-4, the center of gravity of the two arms is found to be 67.76 mm away from the axis of rotation in the x direction. The mass of these two arms is 142.8 g. Therefore, the gravitational forces on those two arms would apply a torque of 0.0948 N.m to the axis of rotation. In the positive x direction, this torque would be acting with the torque applied by the motor, increasing the torque applied on the joystick. In the negative x direction, the torque applied by gravity would be acting against the torque applied by the motor, decreasing the torque applied to the joystick.

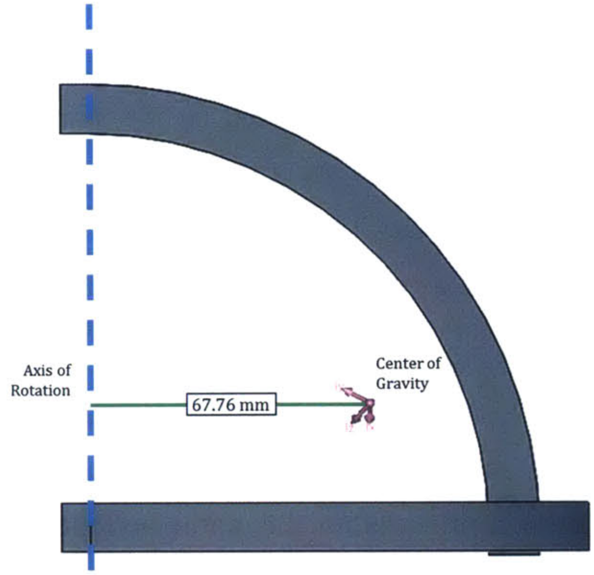

Figure 3-4: A 3D model of two of the joint arms is used to find the center of gravity and mass of these elements. Two of the arms hang to the side of each axis of rotation, applying a torque of 0.0948 N.m about each axis of rotation.

The expected torque applied by the gravity on the device falls within the 95% confidence interval of the offset calculated in the negative x direction. Once the expected torque offset from gravity is applied to each linear fit, the possibility of the linear fit crossing the origin, as it does in the manufacturer's specifications, falls within the 95% confidence interval for both directions.

As shown in figure 3-5, in the y direction, the torques applied were very linearly proportional to the current applied to the motor. However, the slopes of the linear fits applied to the measured data were the same as the slope expected from the limited angle motor given the manufacturer's specifications.

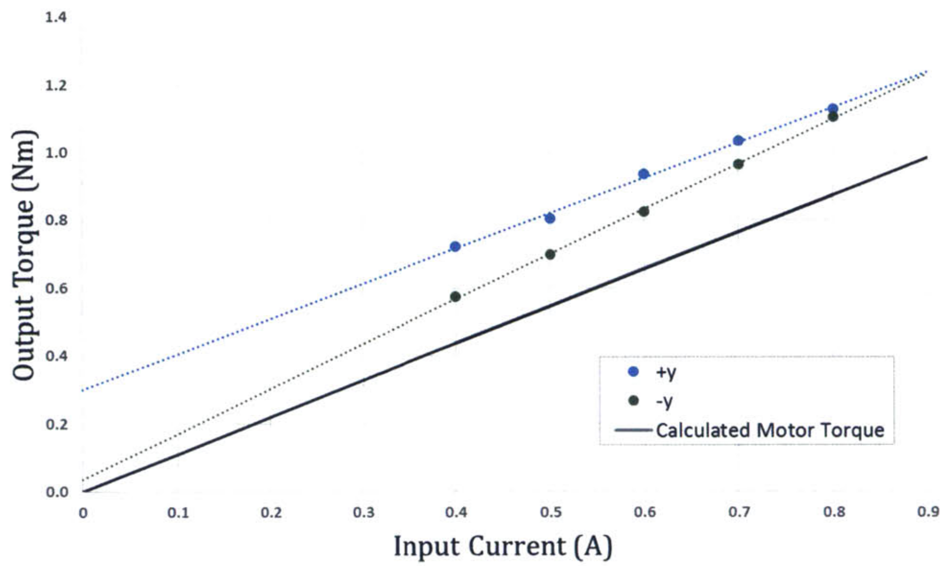

Figure 3-5: The torque exerted by the joystick was calculated by multiplying the measured force by the 140 mm lever-arm. The torque in the positive and negative y directions are above the expected from the limited angle torque motor. The slope of the torque curve in the negative y direction 1.33±0.039 N.m/A is not congruent with the slope specified by the manufacturer for the motor of 1.0945 N.m/A.

The slope of the linear fit applied to the measurements of the torque in the positive x direction is 1.043±0.077 N.m/A. Therefore, the manufacturer's indication of 1.0945 N.m/A falls within the 95% confidence interval. However, the slope of the linear fit in the y direction is 1.33±0.039 N.m/A and the manufacturer's indication does not fall within the 95% confidence interval.

Chapter 4

Conclusion

A 2-axis haptic force feedback joystick was designed through a multi-step design process. The geometric model of a 5-joint apparatus was verified and a full-scale prototype was manufactured. A calibration experiment was performed, revealing the joystick is capable of providing feedback forces proportional to the current applied to the limited angle torque motors, in agreement with the manufacturer's specifications for the motors. However, more extensive calibration must be done to understand the capabilities of the joystick design to provide high-frequency force feedback. The calibration experiments revealed that the gravitational forces on the joystick, which apply torques on each rotational axis, have a significant effect on the force required to withstand the feedback forces applied by each motor. These gravitational effects were identified and found to be consistent with theoretical calculations.

Many other improvements and studies can be done with the joystick apparatus to better understand its characteristics. By mounting an encoder on the backside of each motor, the position of the joystick can be determined in both directions. The joystick can also be connected to other devices or a computer model to verify the functionality of the joystick as a control device. By measuring the frequency response of the joystick system, the viability of the joystick as a haptic force feedback device can be verified.

Improvements in the design for future iterations include reducing the size of each arm, thereby reducing the mass as well. Developing a method for counter-balancing the system may offset the effects of gravity on the design, allowing a more consistent force-feedback response. However, the increased mass may diminish the joystick performance at high frequencies. An improved pivot joint design that better constrains each joint to only a single degree of freedom would also diminish the backlash in the system.

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