ActivSense Sidestick

A Force Sensing and Force Feedback Joystick

by

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Abstract

As aircraft systems continue to become more integrated and fully electronic, hence fly-by-wire, the pilot is slowly losing the physical cues that were once relied upon for the safe operation of the aircraft. Many commercial airliners, such as Airbus, use passive sidesticks that integrate with the electronic flight controls system. These sidesticks move much like a gaming joystick which results in the pilot not having any “feel” for the aerodynamic forces present on the control surfaces. Without the force feedback of a mechanically linked control system the pilot could inadvertently stall the aircraft or place it into an unstable flight condition. To combat this, the active sidestick will include a servo mechanism to provide force feedback and use strain gauges to determine the force applied to the sidestick by the pilot. Multiple sources of data, such as the aircraft configuration and critical speeds can be used to produce a force gradient which resist a pilot’s inputs if they are exceeding the aircraft capabilities.

The active sidestick will interface with PC based flight simulation to control an aircraft and receive flight characteristic data to properly adjust the forces present on the sidestick. Being solely based on force input for aircraft control, if there were to be an in-flight failure of the servos the pilot would still be able to control the aircraft by force alone. Such a sidestick could be used in any number of aviation applications; it would improve the safety of unmanned aircraft operations in which the pilot/operator receives no tactile feedback at the controls. It could also become physically small enough and cost effective to be outfitted in modern general aviation aircraft to prevent the all-too-common loss of control scenario upon landing or takeoff.

Acknowledgements

My senior design project would not have been possible without the support of Cal Poly's Autonomous Flight Lab (AFL). Dr. Aaron Drake of the aerospace department directed AFL funding towards this project which allowed for the purchase of necessary parts and materials. Aerospace engineering graduate student and AFL member Shaun Wixted provided the 3D printing capability. This project culminates a seven-year journey towards a degree in electrical engineering so it is fitting that I also recognize those who provided encouragement and support along the way. Thank you to my parents for doing what they could to make sure that I could focus my attention on my studies. I cannot begin to name all of the friends and family who were present in the pursuit of my degree, but to all of you –

Thank You

Background

Advancement in Aircraft Flight Controls

In traditional, fully analog aircraft the pilots were required to process over a dozen instrument readings and understand the relationship between pitch, power, bank angle and many other vital flight characteristics [1]. This requires a complex scan of multiple instruments to determine the correct control inputs; in some cases, misinterpretation of instrument or physical cues could result in loss of control. Fly-by-wire systems have come into existence not only because of advanced aircraft electronics (avionics) but to assist pilots in control of the aircraft. Fly-by-wire systems implement highly sensitive inertial sensors and computers to command the flight control surfaces to stay on a chosen trajectory and airspeed target [1].

Unfortunately, fly-by-wire systems are not fool-proof and have inherent disadvantages in their current state. In 1988 a French Airbus A320, a popular commercial airliner, crashed at an airshow which was determined to be a result of the innovative fly-by-wire system [2]. The A320 implemented a fly-by-wire system that relied primarily on electrical signals from a sidestick controller; known as a sidestick due to being mounted to the outside edge of the cockpit to avoid interfering with pilot movement [2]. The sidestick sends electrical signals to a computer which translates them into commands for the aircraft control surfaces. In the case of the 1988 accident it was determined that the fly-by-wire system had not failed but rather was caused by loss of control by the pilot. The pilot likely sent the aircraft into a stall without having the physical feedback cues that a mechanically-linked flight control system would provide.

This is where active sidestick, sometimes referred to as active inceptors, come into play. Active sidesticks employ tactile and visual feedback to the pilots. These essential situational awareness cues are missing from many fly-by-wire aircraft such as the aforementioned Airbus A320, Airbus A400M, Dassault Rafale and Embraer Legacy 500 [3]. Active sidesticks allow flight control computers to move both the pilot and copilot sidesticks together as well as when the autopilot makes inputs to the flight control system [3]. Being fully electronic, the sidesticks can be modified in software to provide force feedback that varies the control input effort required at different phases of flight [3].Thus active sidesticks are crucial for filling the gap between traditional, mechanically linked systems to fully fly-by-wire control systems.

Furthermore, as unmanned aircraft technology advances and continues to become popularized, the need for active sidestick systems will continue to increase. Naturally, a person piloting a remotely-piloted aircraft (RPA) is completely removed from the physical feedback loop and has an absolute minimum of situational awareness. In this environment, an active sidestick becomes incredibly important for safety of flight.

Product Description

ActivSense is the next step in responsive, precise control for aerospace and medical applications.

The ActivSense control stick is a common solution to these problems experienced across multiple industries. ActivSense continuously monitors the operator's force input in high fidelity and translates the data into servo driven motion of the control stick as well as drive signals for the end system. ActivSense will also receive data from the end system to properly adjust the force required by the user to move the control stick. With no moving parts required to sense control input there is high repeatability and close to zero hardware failure. In comparison, potentiometer, Hall effect, and inductive sensing technology all have moving parts with very low sensing resolution and are prone to mechanical failure.

The ActivSense sidestick will be differentiated from current solutions by form factor, input/output and multiple marketable applicability. Traditionally an active sidestick might only be found in large aircraft but ActivSense will be designed with unmanned aircraft, medical and general aviation industries in mind. The end user will have greater freedom of tuning the force feedback gradients and can source independent flight data through a standard interface.

Market Research

Current Solutions

A leader in the industry, BAE Systems is providing a commercial active sidestick product to aircraft manufacturers who are willing to take the next step in technology. BAE describes active inceptor systems as providing tactile cueing to pilots by feeding information from the aircraft fly-by-wire system back to the sidestick [4]. BAE Systems created the simplified system diagram of an active inceptor as shown in figure 1 below.

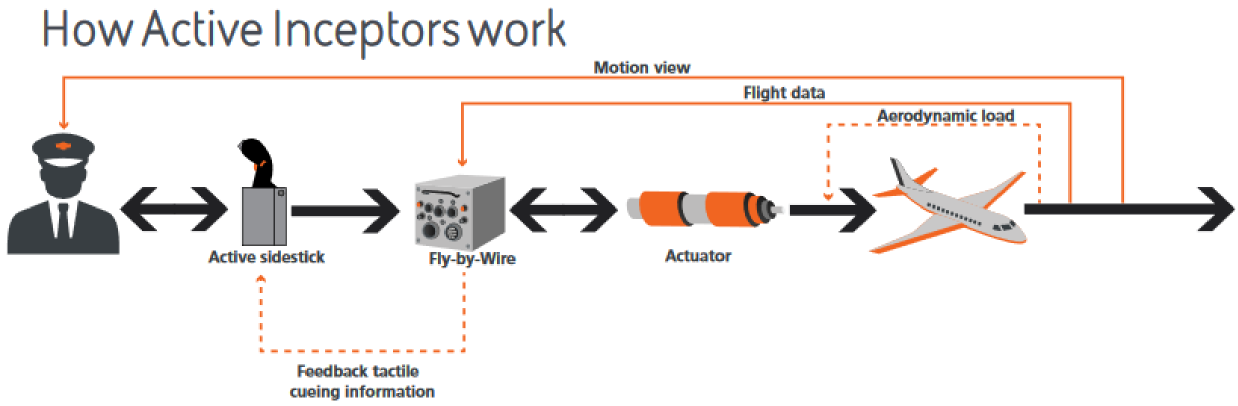
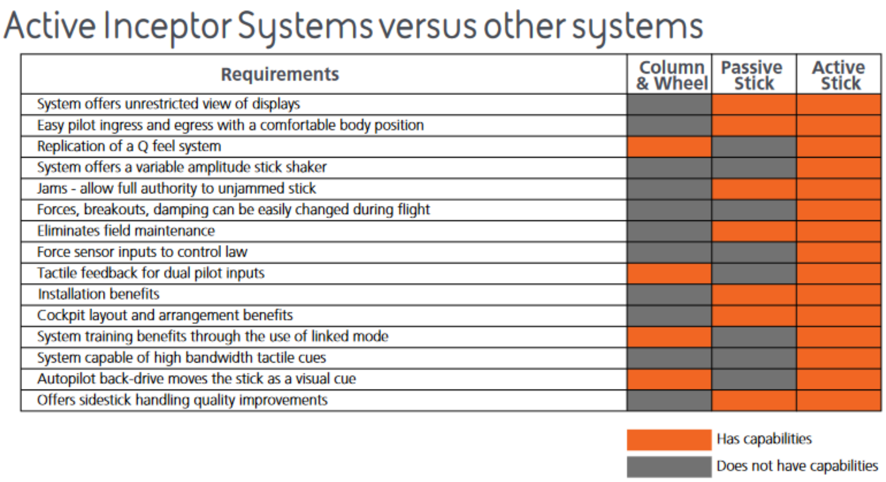


Figure 1- BAE Systems Active Inceptor Diagram [4]

The many benefits of using an active inceptor over a passive electronic sidestick or mechanical controls are clearly defined in the table seen in figure 2 below.



Active Inceptor Systems versus other systems

Requirements	Column & Wheel	Passive Stick	Active Stick
System offers unrestricted view of displays	⬛	🟧	🟧
Easy pilot ingress and egress with a comfortable body position	⬛	🟧	🟧
Replication of a Q feel system	🟧	⬛	🟧
System offers a variable amplitude stick shaker	⬛	⬛	🟧
Jams - allow full authority to unjammed stick	⬛	🟧	🟧
Forces, breakouts, damping can be easily changed during flight	⬛	⬛	🟧
Eliminates field maintenance	⬛	🟧	🟧
Force sensor inputs to control law	⬛	⬛	🟧
Tactile feedback for dual pilot inputs	🟧	⬛	🟧
Installation benefits	⬛	🟧	🟧
Cockpit layout and arrangement benefits	⬛	🟧	🟧
System training benefits through the use of linked mode	🟧	⬛	🟧
System capable of high bandwidth tactile cues	⬛	⬛	🟧
Autopilot back-drive moves the stick as a visual cue	🟧	⬛	🟧
Offers sidestick handling quality improvements	⬛	🟧	🟧

🟧 Has capabilities
⬛ Does not have capabilities

Figure 2- Active Inceptor Advantages [4]

BAE’s system is designed with commercial airliner aircraft in mind. The active inceptor relies on existing fly-by-wire architecture and is physically large. Thus, it is better suited for larger aircraft. What makes BAE’s solution unique is the ability to allow commercial aircraft manufacturers to make use of a technology once reserved for military and space aircraft. For example, business jet manufacturer Gulfstream is implementing BAE’s active inceptors which will mark a first for the entire business jet industry.

Customer Archetype

Commercial Airlines

Commercial airliner manufacturers continue to maintain and deliver aircraft. Airbus has a total of 16,731 deliveries planned for 2016 [5]. With the large number of aircraft being produced there is a large market for installation of active sidesticks before reaching the final customer. Boeing, another prominent aircraft manufacturer, estimates there are over 10,000 Boeing aircraft in service not including recent deliveries [6]. Just considering these two primary aircraft manufacturers it is evident there is a possibility for a significant market share in manufacturing and retrofit businesses. These prospective customers would benefit from the additional safety made possible by active sidesticks. Public exposure to these technologies may also result in greater peace of mind in airline passengers.

Defense Industry

There are a few avenues into the defense industry to be considered. While the active sidestick technology is not a new concept in military aircraft most airframes employed by the armed forces do not take advantage of this technology. Unmanned aircraft would see a decrease in mishaps if active sidesticks were implemented in the ground control stations. General Atomics, the dominant unmanned aircraft manufacturer, supports 678 drones currently in use by the military [7]. With unmanned aircraft technology still reaching maturity it is the optimal time to introduce the active sidestick technology. Remotely piloted aircraft (RPA) operators would benefit from the tactile feedback; in addition to a remote visual feed, the pilot would receive force feedback to confirm the movement they perceive visually. With millions being spent on the maintenance and new acquisitions of RPAs there is an obvious benefit to the U.S. Department of Defense to invest in active sidestick technology; mishaps and expensive accidents would be reduced.

General Aviation

While it is the smallest market there is still a great benefit to be had by general aviation if active sidesticks are adopted. It would be difficult to integrate the technology into traditionally analog aircraft such as early model Cessna aircraft, but much easier for late model aircraft. As an example, Cirrus Aircraft builds a production line aircraft that incorporates a sidestick and glass cockpit displays. Cirrus models such as the SR-22 famously incorporate a parachute into the airframe; the next step in safety would be implementing the active sidestick. Cirrus aircraft are uniquely situated to make this possible as they already have digital autopilot and instrument systems. Outside of certified production aircraft, it would be easier to incorporate active sidesticks into experimental aircraft. With fewer Federal Aviation Administration (FAA) regulations it would be the ideal starting point for introducing these sidesticks into the general aviation market.

Market Share

While there is a large a number of commercial aircraft currently in service, this segment is not expected to make up the largest market share. Retrofit and stringent certification requirements by the FAA will severely limit the ability of airlines to implement the technology in airliners currently being operated. Military aircraft are less hindered by such restrictions; thus, the defense industry is expected to have the most significant market share. Given the number of aircraft in operation for each industry, the following market share diagram was developed.

Currently BAE Systems is the market leader in foreign defense and commercial aircraft manufacturers. Lockheed Martin, a defense contractor, manufactures the F-35 fighter jet which incorporates an active sidestick.

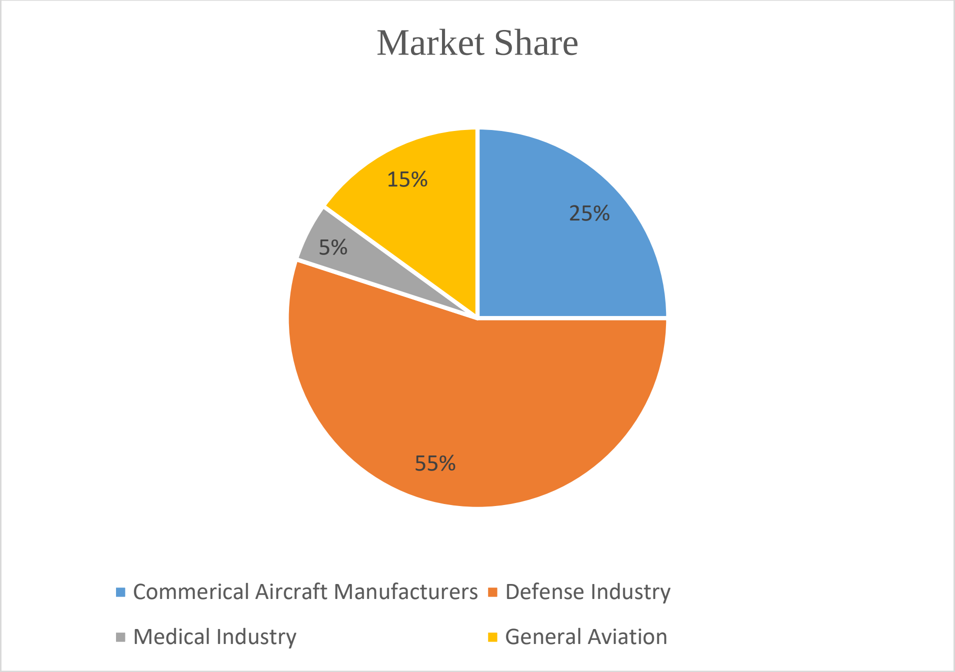
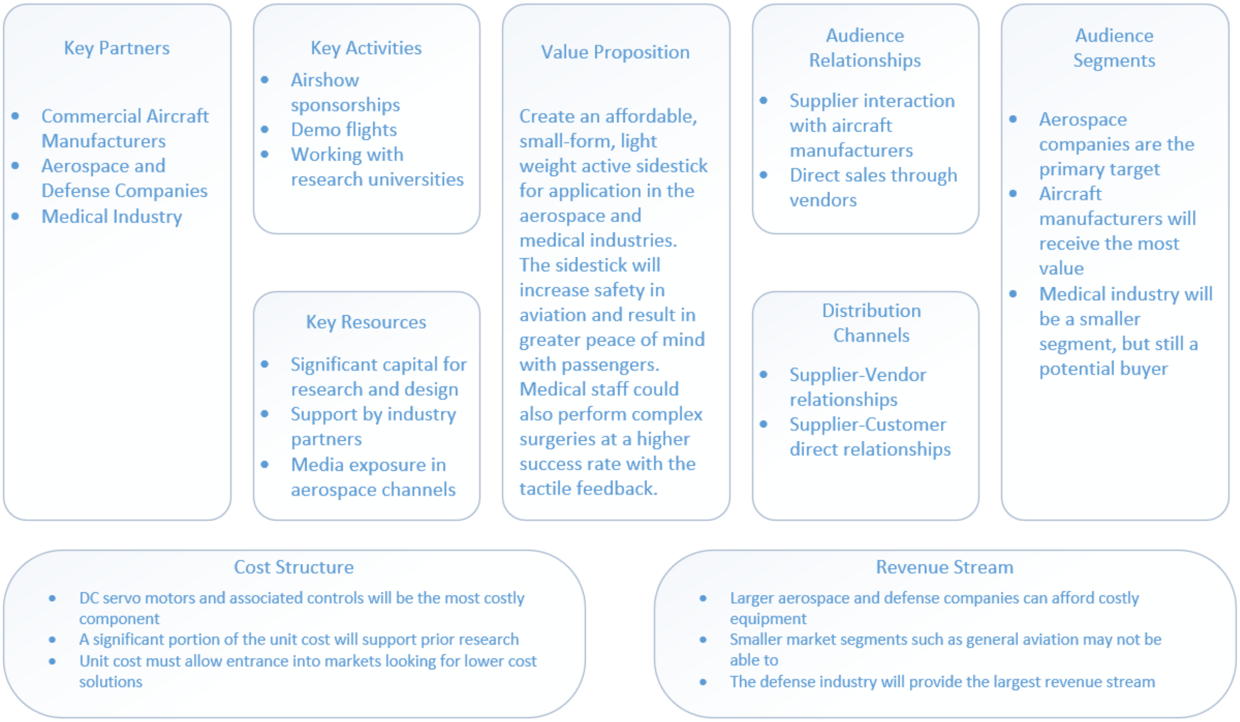


Figure 3- Market Share Pie Chart

Business Model Canvas



Key Partners

- Commercial Aircraft Manufacturers
- Aerospace and Defense Companies
- Medical Industry

Key Activities

- Airshow sponsorships
- Demo flights
- Working with research universities

Key Resources

- Significant capital for research and design
- Support by industry partners
- Media exposure in aerospace channels

Value Proposition

Create an affordable, small-form, light weight active sidestick for application in the aerospace and medical industries. The sidestick will increase safety in aviation and result in greater peace of mind with passengers. Medical staff could also perform complex surgeries at a higher success rate with the tactile feedback.

Audience Relationships

- Supplier interaction with aircraft manufacturers
- Direct sales through vendors

Distribution Channels

- Supplier-Vendor relationships
- Supplier-Customer direct relationships

Audience Segments

- Aerospace companies are the primary target
- Aircraft manufacturers will receive the most value
- Medical industry will be a smaller segment, but still a potential buyer

Cost Structure

- DC servo motors and associated controls will be the most costly component
- A significant portion of the unit cost will support prior research
- Unit cost must allow entrance into markets looking for lower cost solutions

Revenue Stream

- Larger aerospace and defense companies can afford costly equipment
- Smaller market segments such as general aviation may not be able to
- The defense industry will provide the largest revenue stream

Figure 4- Business Model Canvas

Marketing Requirements

Customer Need	Importance	Applicable Features
Programmable force gradients	Aircraft manufacturers should have the freedom to adjust the force feedback to be realistic for different airframes	USB, RS-232 or RS-485 standard aerospace interfaces for compatibility with avionics and computers
Redundancy	Should the equipment fail mechanically the pilot should still be able to control the aircraft	Electronic strain gauges, which do not move, will allow the pilot to control the flight surfaces regardless of whether or not the servos are operational
Small form factor	Space and weight are both expensive aspects of aircraft design – they must both be minimized.	The sidestick mechanism, including all required servos, should fit into a rectangular form factor not to exceed 24 x 24 inches.
Compatibility with existing avionics architecture	All aircraft follow a standard interface as defined by ARINC, an industry standard such as IEEE	USB, RS-232 or RS-485 standard aerospace interfaces for compatibility with ARINC 429 or ARINC 664 data bus architecture

Table 1- Customer Needs Table

Programmable Force Gradients

With force feedback at the heart of the active sidestick technology it is important that this feature be user programmable. User is defined in this context as a manufacturer, not a pilot. A jet powered commercial airliner will clearly have different handling qualities than a smaller twin piston engine aircraft. It is important that the active sidestick can then be adjust to have different force responses or gradients depending on the aircraft type; for example, the sidestick should be programmed to have a “heavier” feel in a large commercial airliner and a “lighter” feel in an aircraft half the size which is more maneuverable. Electronic steering in automobiles is analogous to this concept; a semi-truck with electronic steering should not be able to steer as freely as a small automobile with the same technology.

Redundancy

A factor stressed in all aspects of avionics and aircraft development is common mode failure avoidance and multiple redundancies. There should not be one point of failure that would result in uncontrollability. The active sidestick is naturally redundant in that physical movement of the stick is not required for electronic control of the flight surfaces; movement only serves the purpose of force feedback. Multiple strain gauges will be used to sense force input such that there are multiple channels to receive the pilot’s control input. In case of any failure, the pilot will be alerted using a Crew Alerting Message (CAS) that is standard in large aircraft cockpits.

Small Form Factor

The active sidestick is going to be targeted for many different airframes which may vary from a spacious cockpit to a much more compact cockpit. The final product must be designed to fit in small spaces and not occupy valuable real estate in the cockpit. Aside from the size, weight is also an important consideration in aircraft. The aircraft has a weight and balance calculation accomplished anytime a modification is made that might vary the weight greater than a few pounds. Greater weight also means higher fuel consumption and a high cost passed along to the end customer.

Avionics Backward Compatibility

The aerospace industry follows a standard set by Aeronautical Radio, Incorporated (ARINC) when designing both avionics and human machine interfaces. Two common data bus standards that the active sidestick will be required to interface with are ARINC 429 and ARINC 664 [8]. ARINC 429 is less complex and invokes a two-wire bus interface as depicted in the following figure. Multiple units, such as the active sidestick, can communicate on the two-wire bus that extends the entire aircraft.

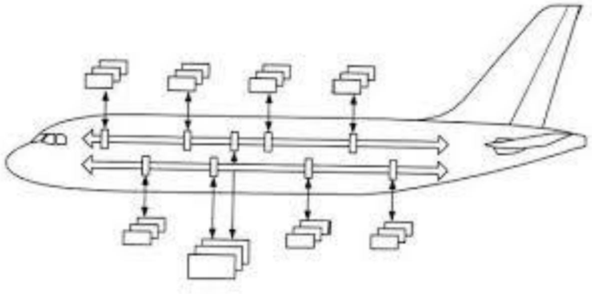
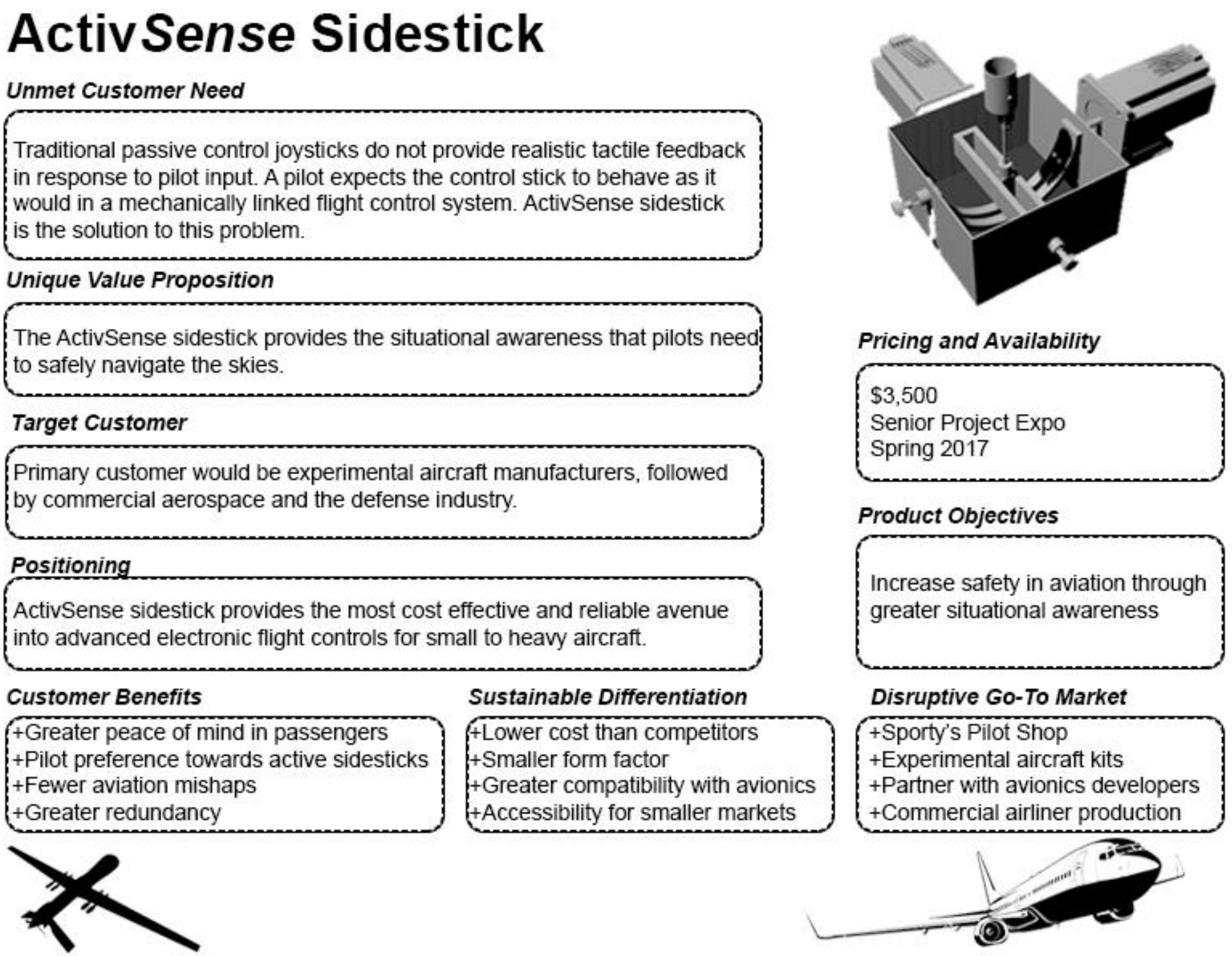


Figure 5- ARINC 429 Bus Topology

ARINC 664 is more complex protocol that is like Ethernet; a unit is required for routing the signals or assigning ports to line replaceable units (LRU). This method is becoming more common in larger aircraft. The active sidestick should can interface with both data bus architectures. A separate port should also be implemented to allow direct connection to a computer.



Activ*Sense* Sidestick

Unmet Customer Need

Traditional passive control joysticks do not provide realistic tactile feedback in response to pilot input. A pilot expects the control stick to behave as it would in a mechanically linked flight control system. ActivSense sidestick is the solution to this problem.

Unique Value Proposition

The ActivSense sidestick provides the situational awareness that pilots need to safely navigate the skies.

Target Customer

Primary customer would be experimental aircraft manufacturers, followed by commercial aerospace and the defense industry.

Positioning

ActivSense sidestick provides the most cost effective and reliable avenue into advanced electronic flight controls for small to heavy aircraft.

Pricing and Availability

$3,500
Senior Project Expo
Spring 2017

Product Objectives

Increase safety in aviation through greater situational awareness

Customer Benefits

+Greater peace of mind in passengers
+Pilot preference towards active sidesticks
+Fewer aviation mishaps
+Greater redundancy

Sustainable Differentiation

+Lower cost than competitors
+Smaller form factor
+Greater compatibility with avionics
+Accessibility for smaller markets

Disruptive Go-To Market

+Sporty's Pilot Shop
+Experimental aircraft kits
+Partner with avionics developers
+Commercial airliner production

Figure 6- Marketing Data Sheet

System Diagrams

Level 0 Diagram

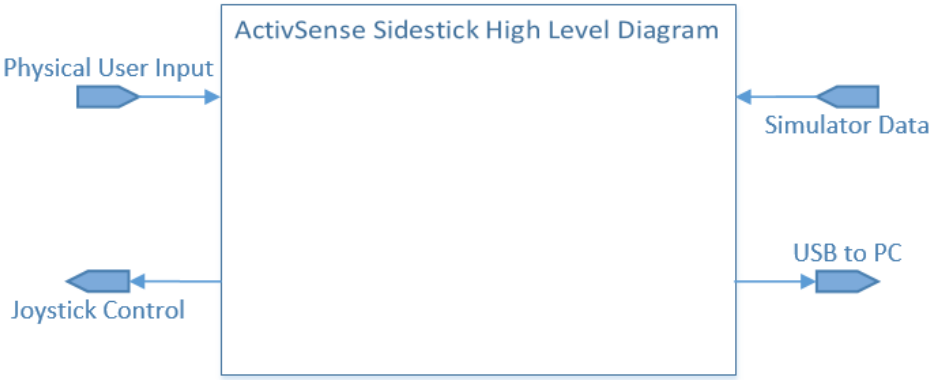


Figure 7- Level 0 Black Box Diagram

Level 1 Diagram

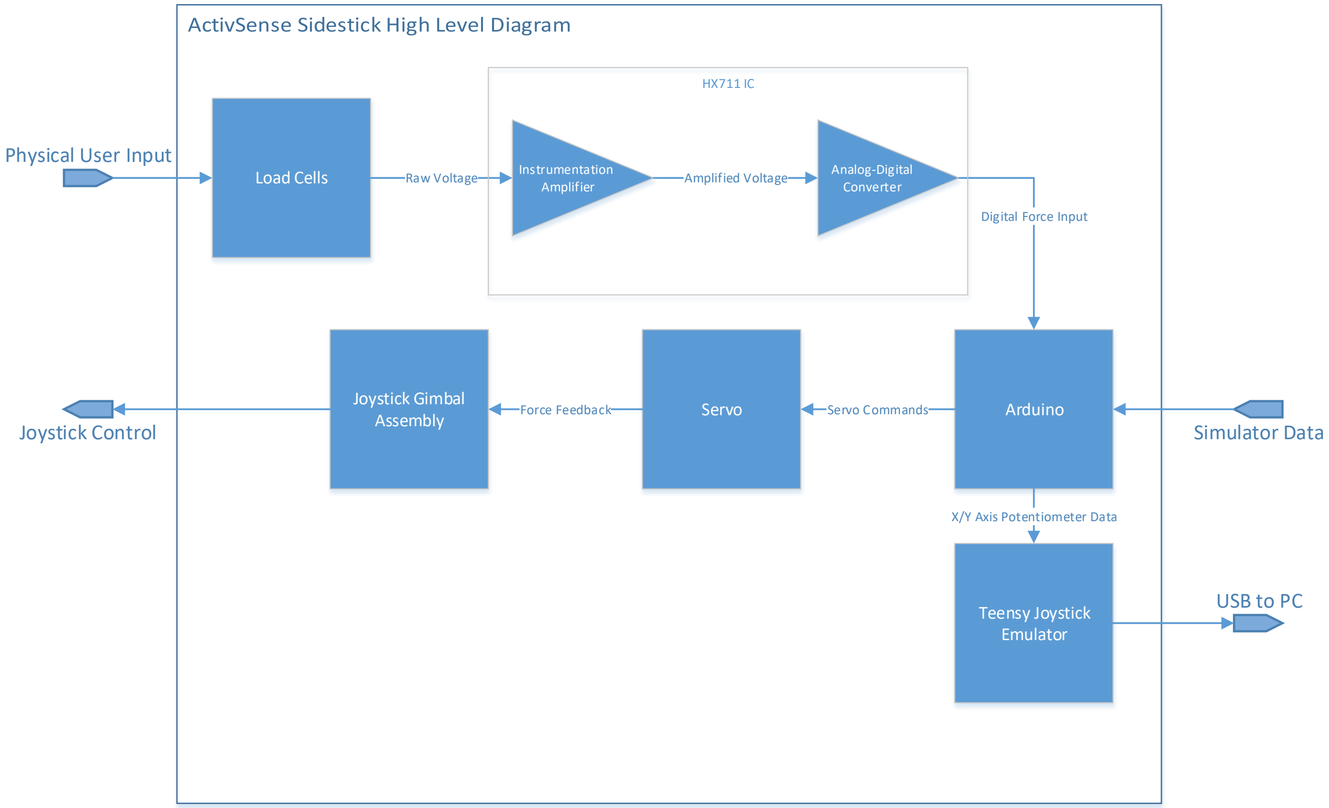


Figure 8 – Level 1 System Diagram

User Input

The system receives physical user input directly from the joystick mechanism. The user force is translated to an electrical signal using load cell sensors. The signals will require significant conditioning and conversion to the digital domain further along in the system as can be seen in the block diagram.

Joystick Control

One of the two outputs provided by the system is the joystick control. After sensing the user input and comparing it with simulator data, the microcontroller will command a servo to drive the movement of the joystick. In this sense, the user is not moving the joystick physically but rather the microcontroller has full authority over its’ motion.

Simulator Data

The system will also require input data from an external flight simulator to provide realistic force feedback to the user. This input is unique to the prototype of this system; in final release, the simulator data would ideally be multiple inputs from the aircraft data bus.

USB to PC

The USB output is designed for interfacing with a PC. The PC will recognize the sidestick as a human interface device (HID) similar to how a gaming joystick works. This will close the loop between the flight simulator and sidestick system allowing full testing capability in flight conditions that would not be safe in a real-world environment.

Software Functional Diagram

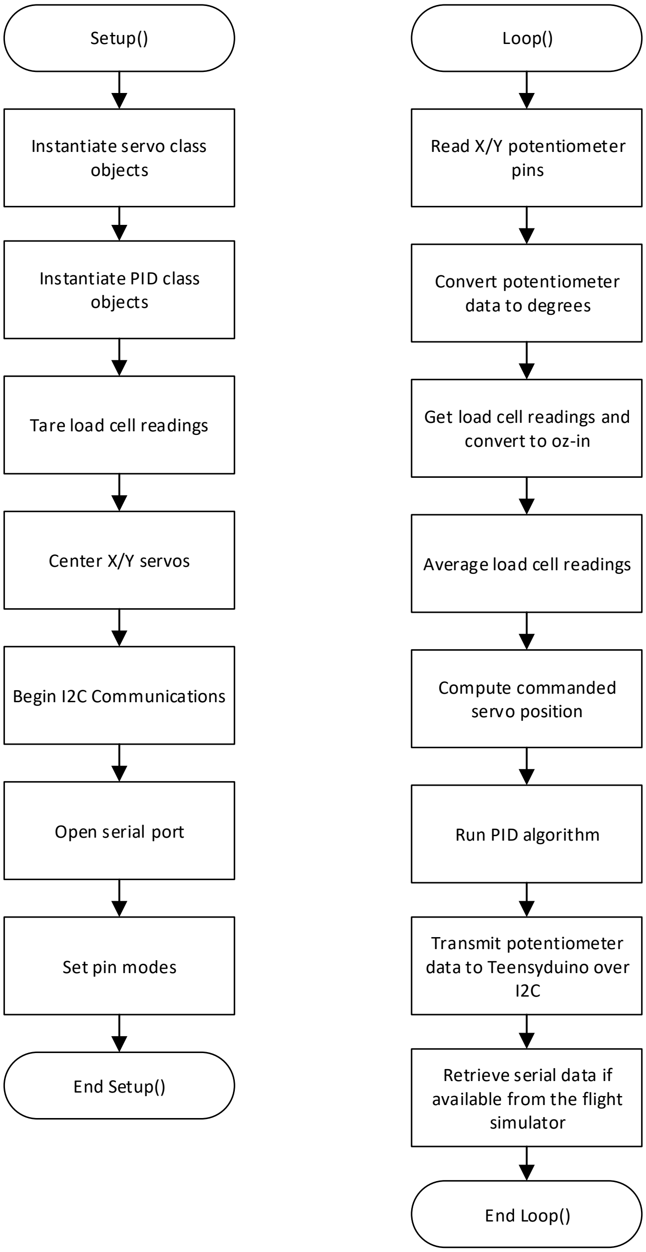


Figure 9 - Software Flow Diagram

System Requirements

Requirement I.D.	Linked Market Requirement	Engineering Requirement
1.0.0	User programmable force gradients	The sidestick shall have standard USB interface for programming by PC
1.0.1	Simulator connectivity	The sidestick software shall be compatible with PC flight simulators
1.1.0	Avionics backward compatibility	The sidestick shall interface at least with ARINC 429 data bus topology
1.2.0	Redundancy	The sidestick shall have full controllability in the event of servo or mechanical failure
1.2.1	Redundancy	The sidestick shall incorporate independent power supplies for the servos and logic devices in case of faults
1.3.0	Small form factor	The sidestick shall not exceed a rectangular form factor of size 24 x 24 x 24 inches
1.3.1	Small form factor	The sidestick shall have a grip that can be interchanged for right or left handed operation

Table 2 - Engineering Requirements

System Design

Hardware Design

Load Cell

A dual axis load cell was required to measure the amount of force applied in both the *x* and *y* axes. Designing such a load cell requires careful thought into the mechanical design such that force is distributed across the structure correctly; furthermore, manual placement of strain gauges on the load cell body requires great precision to allow the strain measurement of each axis to be linear and repeatable. Rather than designing such a load cell from scratch, a readily available load cell was chosen from the market. The M200 Dual Cantilever Load Cell by Strain Measurement Devices was chosen for its small size and dual axis measurement ability. The M200 is limited to 28 N-cm which limits its use in this application. To minimize the applied torque a special grip was designed.

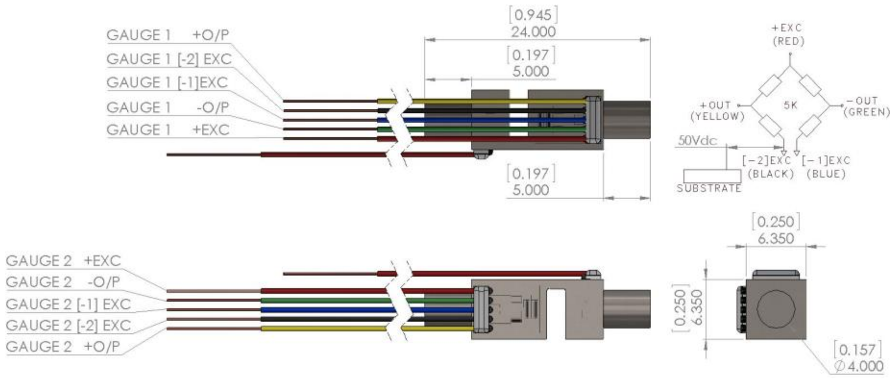


Figure 10 - SMD Sensors M200 Load Cell [9]

Strain Gauge Measurement

The full Wheatstone bridge configuration of the M200 load cell is not well suited for direct measurement of resistance or differential voltage. With 10 VDC excitation voltage the datasheet states the full scale output is 1.4 mV/V nominally. An excitation voltage of 5 VDC was chosen for this application due to its availability from the microcontroller; at this voltage the full scale output will be much less. To accurately measure and convert the differential voltage an instrumentation amplifier and analog to digital converter is required. To minimize the possibility of errors and noise from discrete components, the AVIA Semiconductor HX711 integrated circuit was chosen. The HX711 incorporates a 24-bit sigma delta ADC and programmable gain amplifier.

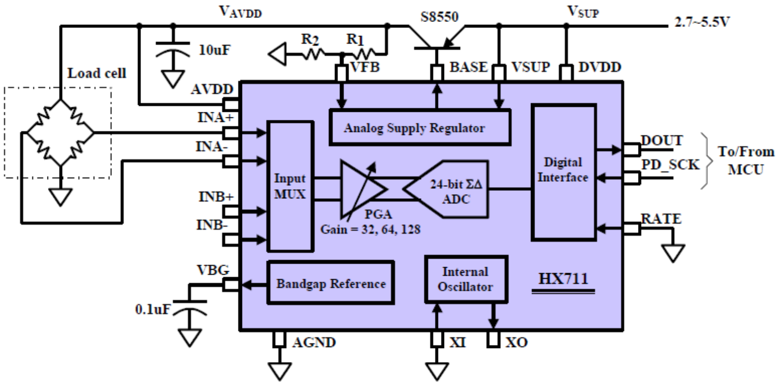


Figure 11- HX711 Schematic [10]

SparkFun Electronics breakout board for the HX711 was purchased to speed the integration of the HX711. The breakout board also incorporates filtering of the digital power rail to further reduce noise susceptibility.

Gimbal Mechanism

A gimbal must be used to provide two degrees of freedom; the gimbal must also allow attachment of one servo and potentiometer for each axis. Without the use of complex gear boxes the most common gimbals on the market would not work for this application. The final gimbal design was adapted from examining several joystick gimbal mechanisms widely available on the market. The gimbal was completely designed in Blender 3D freeware software. The entire gimbal is made up of three moving parts; two of which have 8mm shafts for the direct attachment of a servo and potentiometer on opposite ends.

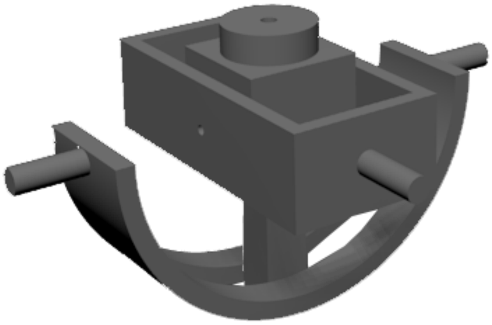


Figure 12 – Gimbal 3D Model

Due to the complexity of the gimbal it was manufactured using 3D printing. The printed model then had 8mm bearings attached to the shafts to allow smooth rotation on both axes.

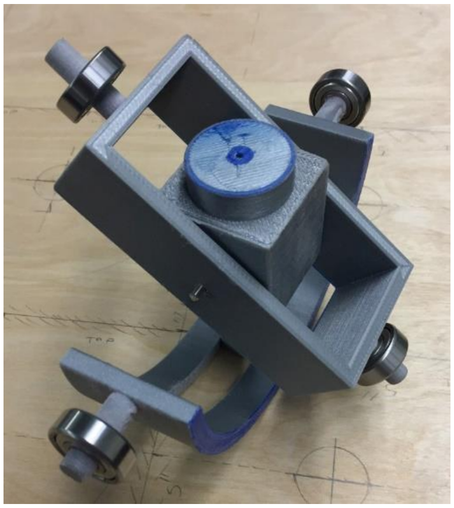


Figure 13 - 3D Printed Gimbal Assembly

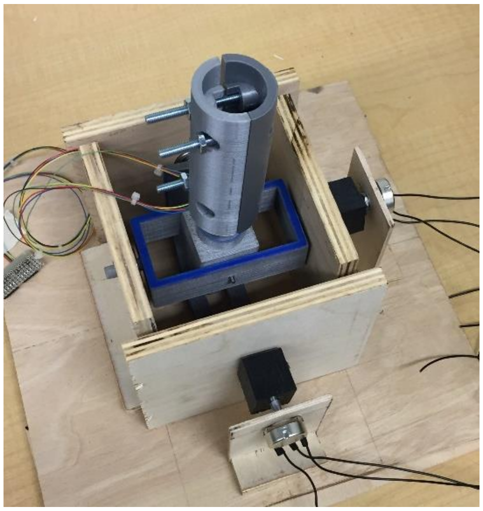


Figure 14 - Mounted Gimbal

Sidestick Grip

The M200 load cell has a 28 N-cm maximum force specification and 200% overload. To reduce the amount of force applied to the load cell the grip had to be designed to focus the force at the tip of the load cell. The grip was made in two pieces; when separated, the load cell can be placed directly inside the grip. The 4mm shaft of the load cell is inserted into the grip which directs all the force to the tip of the load cell.

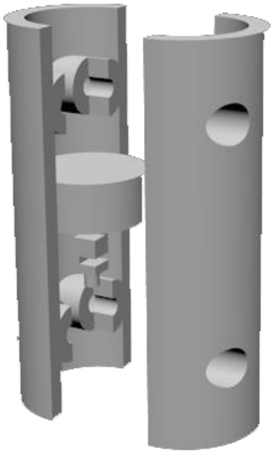


Figure 15 - Grip 3D Model

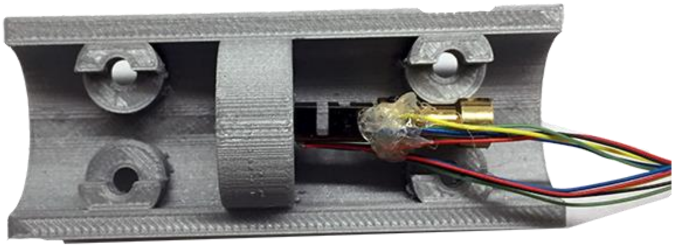


Figure 16 - 3D Printed Grip with Load Cell Attached

Servos

The servos for both the X and Y axes had to be selected to withstand the force applied by the pilot along with additional torque required for force feedback. Provided the funding, there are many DC servo motors on the market that could provide over 100 in-lb of torque to the gimbal shaft. Given the financial limitations of this project, a suitable remote-control application servo was chosen. The Savox SA-1283SG steel gear servo can provide up to 347.2 oz-in of torque at a supply voltage of 4.7V. The digital servo is operated by the microcontroller using pulse width modulation.

Figure 17 - Savox SA-1283SG Servo [11]

USB Human Interface Device (HID)

To complete the loop between the flight simulator and sidestick the system required a USB output to the PC that could act as a joystick. Having the primary microcontroller connect to the PC and send joystick commands would hamper the fast processing speed required for the control algorithm. To offload this process from the microcontroller the TeensyDuino 3.2 was selected to be used solely as a joystick input for the PC. TeensyDuino can be programmed to present itself as a human interface device (HID) to the PC when connected via USB. It will read in the potentiometer voltages and scale the digitally converted data. For the X and Y axes, the PC recognizes an integer value of 1024 as max deflection; thus, the potentiometer readings will be calibrated to provide full scale deflection for the useable X and Y ranges of the gimbal.

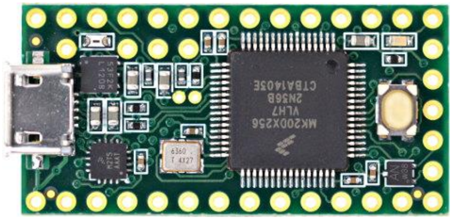


Figure 18 - TeensyDuino 3.2 [12]

Microcontroller

The Arduino Mega 2560 was chosen as the primary microcontroller for the entire system. This board is based on the Atmel ATmega2560 microcontroller. It was primarily chosen for the number of analog inputs available. There are 54 digital I/O pins and 16 analog I/O pins. A 16 MHz onboard oscillator will be sufficient to handle serial communications and servo control at a rate that will not create a noticeable lag to the user.

Prototype Board

A prototype board was developed as an Arduino shield. The board connects the two HX711 devices, load cell Wheatstone bridges, potentiometers, servos and DC power supply to the Arduino using header pins. Future improvements would be a PCB that incorporates all of the devices.

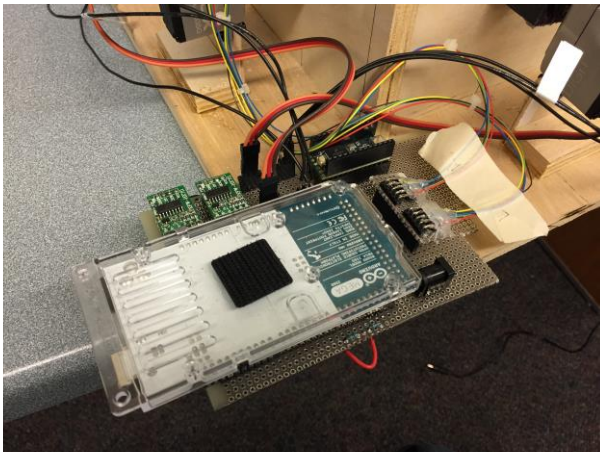


Figure 19 - Prototype Board (Top)

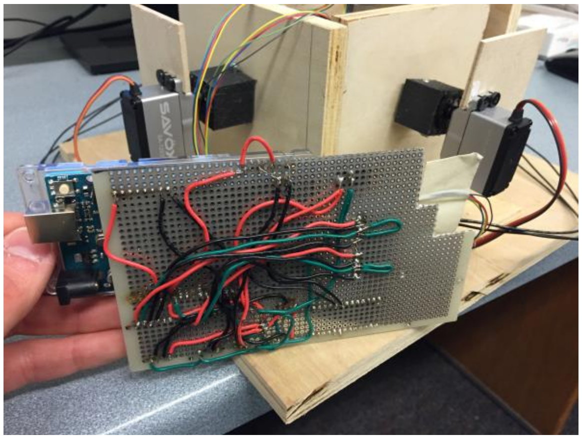


Figure 20 - Prototype Board (Bottom)

Windows User GUI

Lockheed Martin Prepar3D® Interface

The flight simulator of choice for this project, Prepar3D®, has an interface library provided by Lockheed Martin. The library, SimConnect, allows third party software to read flight simulation variables or command the flight simulator directly. SimConnect is used in this project to gather the flight simulation variables for transmission to the Arduino. Internal flight simulation variables must be subscribed to before they can be requested by external applications. For this project, the aircraft altitude, airspeed and barometer are requested. SimConnect allows a data query at a 6 Hz rate which will limit the speed at which the data can be transmitted to the Arduino.

Arduino Serial Communication

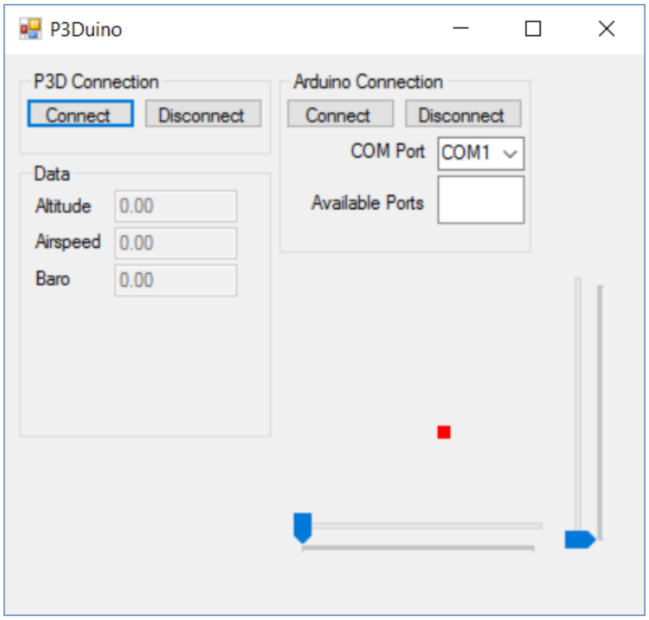
Two-way communication with the Arduino and simulator host PC is required for sending flight simulation variables and debugging information. Serial communication is established with the Arduino by opening the COM port that the Arduino is associated with. A list of possible COM ports is provided to the user. A timer is attached to the GUI to initiate a serial transmission every 170ms, or just below 6 Hz. This is to allow the flight simulation variables to refresh before every transmission which occurs at a 6 Hz rate as defined in the SimConnect library. The data is then packed into a string and sent over the serial connection. If serial data is received from the Arduino, the data will be processed in the reverse manner.

GUI Functionality and Layout

The GUI allows the user to establish communication with the Arduino and simulator independently. The individual fields are described in Table 3.

Field Name	Options	Description
P3D Connection	Connect	Connect to Prepar3D
	Disconnect	Disconnect from Prepar3D
Arduino Connection	Connect	Connect to the Arduino
	Disconnect	Disconnect from the Arduino
	COM Port	COM port for communication with Arduino
	Available Ports	List of currently available COM ports
Data	Altitude	Aircraft altitude above sea level
	Airspeed	Aircraft true airspeed
	Baro	Kohlsman Barometer Setting
Joystick	Sliders	Displays the X and Y joystick deflection value
	Red Square	Moves per the commanded joystick movement

Table 3 - GUI Interface Description



Altitude 0.00
Airspeed 0.00
Baro 0.00
COM Port COM1

Figure 21 - Windows User GUI

Force Feedback Concept

With force as the input to the system a relationship is required to translate force to commanded servo position. An initial relation was defined by the following equation:

$$Servo\ Position = \sqrt{\frac{Force\ [oz - in]}{K_G}} \quad [°]$$

$$K_G = Force\ Gradient\ Constant$$

Equation 1 - Force and Position Relation

The force gradient constant, K_G, was selected such that a maximum applied force of 150 oz-in would produce the maximum servo displacement of 25°. Servo position is considered as displacement from the center position. The relationship was plotted in Figure 22. It can be seen that only a small amount of force is required to increase the servo displacement from center. As the servo position moves further from center it requires much more force to continue to the movement. Three data sets were plotted with K_G = 0.24, 0.34 and 0.14. A larger K_G increases the amount of force required to move the servo from the center position.

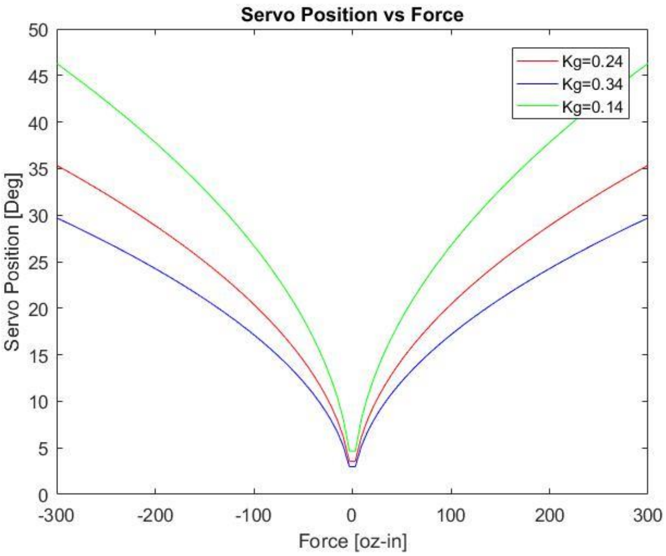


Figure 22 - Servo Position vs Force Graph

The force constant will be varied in response to changing flight variables. For example, during slow flight the force needed to move the stick should be minimal to mimic the sluggish response of traditional flight controls. At the other extreme, high speed flight, the stick should be harder to move because any large inputs to the flight controls will result in over controlling the aircraft. Figure 23 depicts both scenarios graphically.

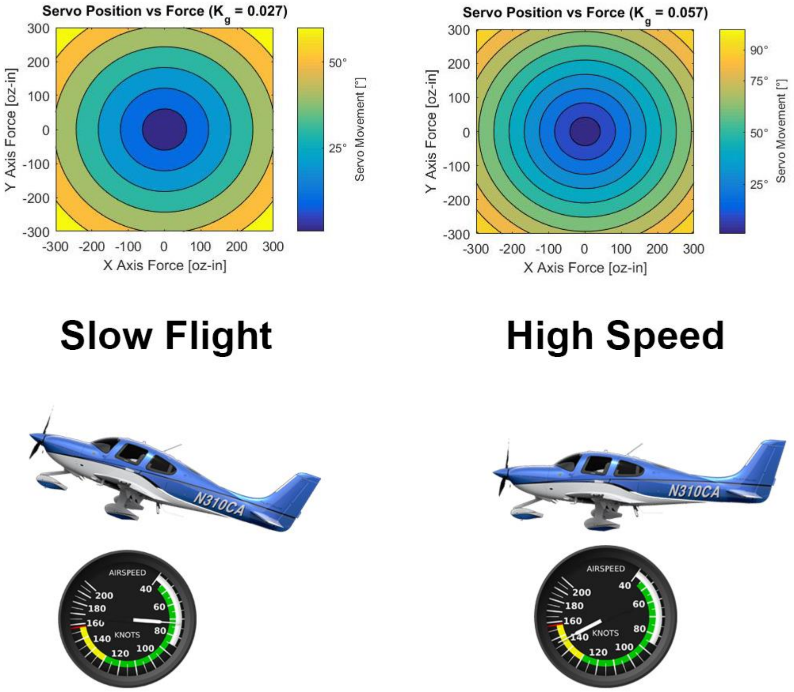


Figure 23 - In-flight Force Feedback Visualization

Control System Design

A PID controller is required for both the X and Y axis servos attached to the gimbal assembly. The feedback loop is provided by the potentiometers on each axis; each potentiometer has been calibrated to provide a known voltage to position relationship. The microcontroller will read in the feedback voltage and determine the corresponding position in degrees. The servo itself is modeled as a second order system using the specifications provided in the datasheet. See the Servo Characterization heading for information on how this was accomplished. The HX711 devices will be used to read in the current force being applied to each axis. This force is then converted to an appropriate servo command in degrees. For information on this force to position relationship see the heading Force Feedback Concept. Given that most of the control variables are readily available as continuous, analog signals the control system would be well suited for a completely analog PID controller. In this project, it was elected to perform all processes within the microcontroller. A library was written for the microcontroller to perform the PID functions. The library calculates the derivative, proportional and integral portions of the system and sums them for output to the servos. A simplified software flow diagram for the PID library is shown in Figure 24.

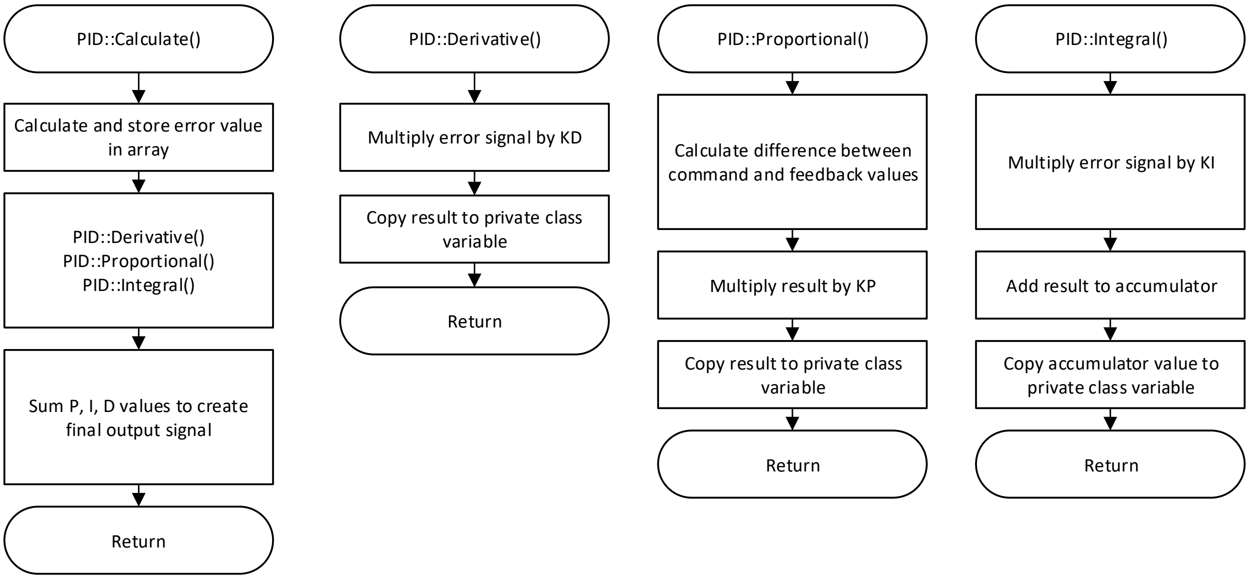


Figure 24 - PID Software Flow Diagram

To approximate the derivative and integration functions within the PID library the following equations were used.

$$\frac{d}{dt}e[n] \approx \frac{\Delta Error}{\Delta Time} \approx T_{Sample} \times (e[n] - e[n-1])$$

Equation 2 - Approximate Derivative Equation

$$\int e[n] = \sum e[n] \times T_{Sample}$$

Equation 3 - Approximate Integral Equation

A high-level diagram of the control system is shown in Figure 25. The signal flow from the load cell to the servos and the feedback loop are illustrated. The simulated system in Matlab is described in further detail under Simulink System Model.

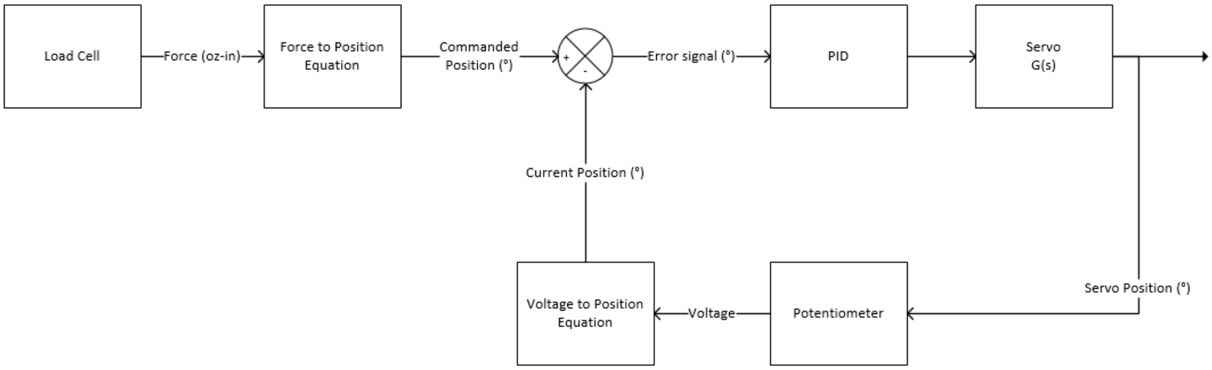


Figure 25 - Control System Diagram

System Component Characterization

Load Cell Characterization

Before the load cell could be used it had to be tested for linearity and response to applied force. Linearity is important to this application; without a repeatable and linear response, a control algorithm would be difficult to implement. To test the load cell a fish scale was used to apply force at defined intervals while measuring the differential voltage from the Wheatstone bridge as well as raw ADC output. Both axes of the load cell were found to be linear and accurate; each axis had a different slope of millivolt per unit force which will be taken into account with the control algorithm.

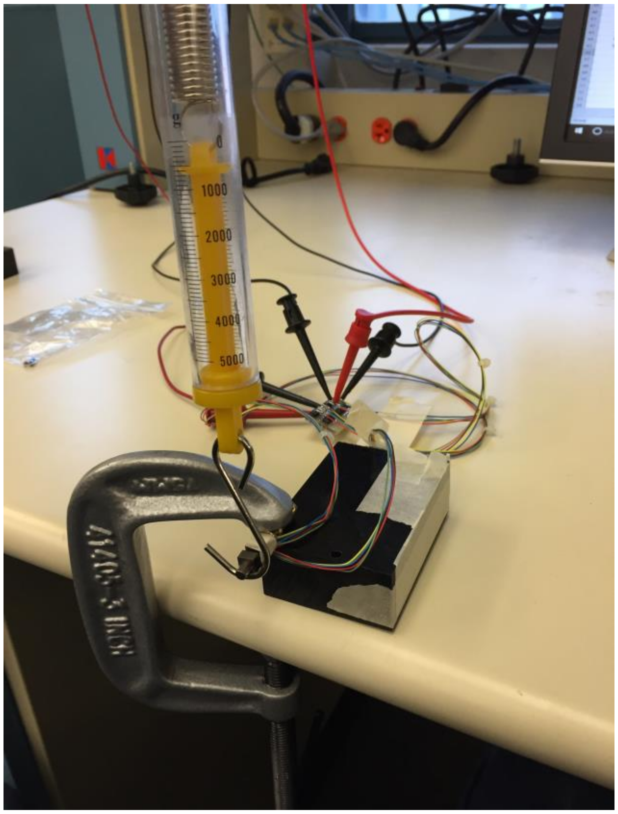


Figure 26 - Test Setup for Load Cell

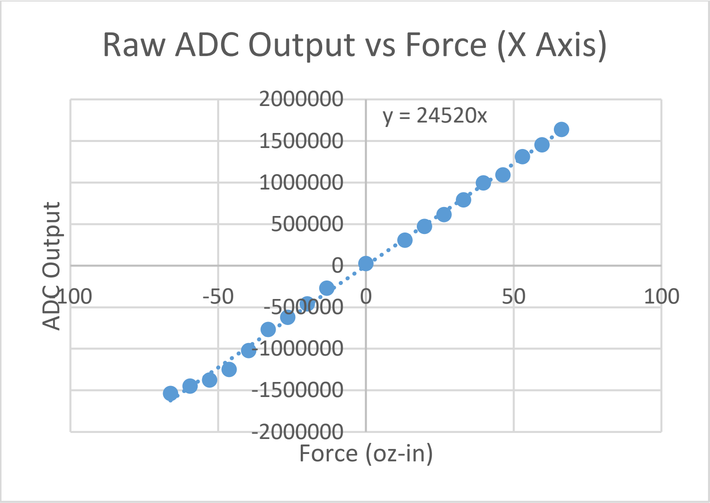


Figure 27 - ADC Output (X Axis)

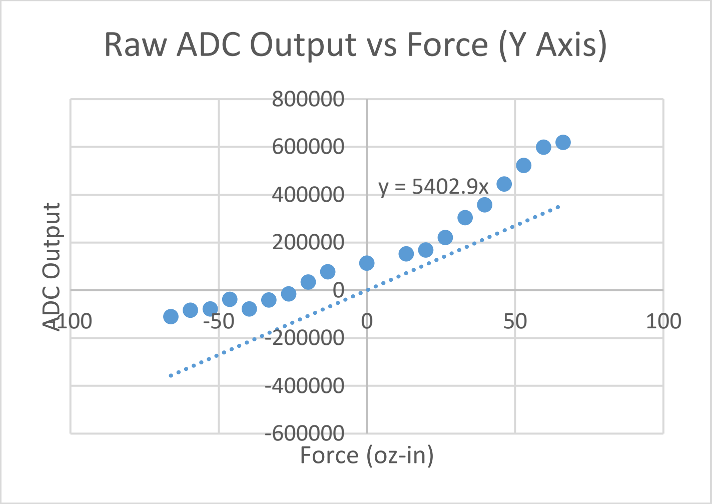


Figure 28- ADC Output (Y Axis)

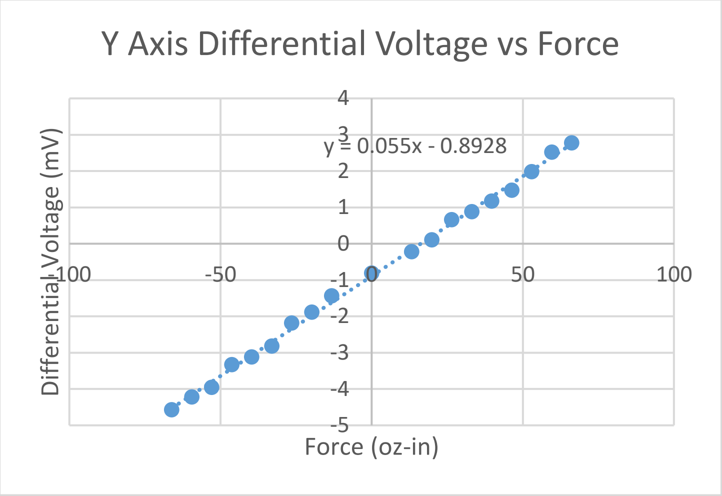


Figure 29 - Differential Voltage vs Force (Y Axis)

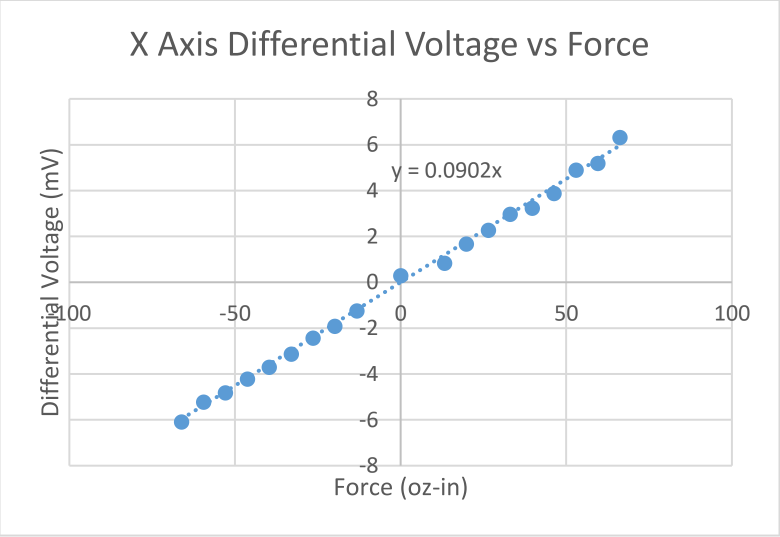


Figure 30 - Differential Voltage vs Force (X Axis)

Potentiometer Range Scaling

Before the potentiometers can be used for position sensing they must be calibrated to the range of movement available from the gimbal. Each 10kΩ linear taper potentiometer was set to approximately 5kΩ when each axis is centered. It is desired to translate the potentiometer reading to degrees of displacement from the center position; to accomplish this, the ADC output from each potentiometer was read at three different intervals – center position, full forward deflection, full backward deflection. The displacement in degrees from center was read using a protractor. Plotting the degrees of displacement per ADC output we can generate an equation to translate the ADC output to a position in degrees. The position sensing serves a secondary purpose as joystick commands to the flight simulator host PC. A full-scale deflection for any joystick axis corresponds to 1024 and a center value of 512. With this information, we are also able to determine a relationship to translate potentiometer ADC readings to digital joystick position. The following readings were taken to accomplish both tasks:

Y Axis		
ADC Reading	Degrees of Displacement	Joystick Position
891	65	1024
668	0	512
430	-65	0
X Axis		
ADC Reading	Degrees of Displacement	Joystick Position
895	50	1024
800	0	512
536	-50	0

Table 4- Potentiometer Calibration Data

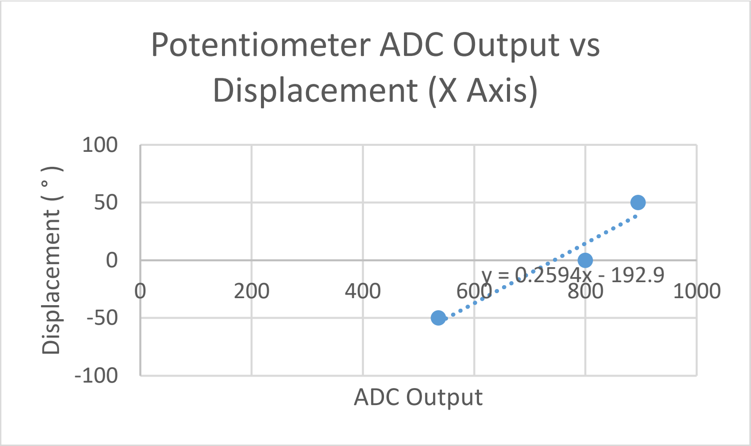


Figure 31 - Potentiometer ADC Output (X Axis)

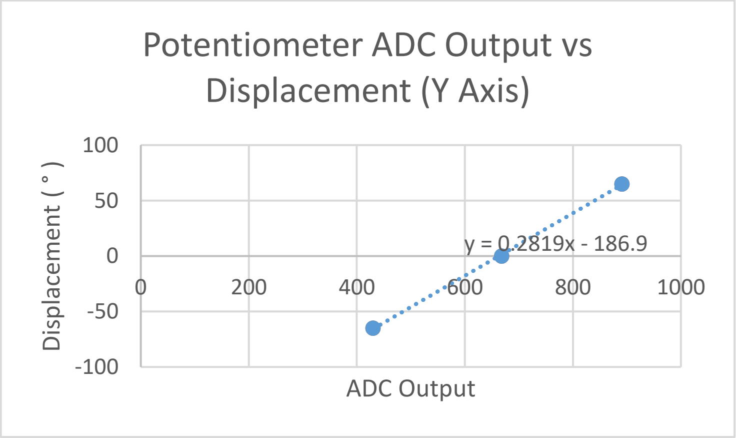


Figure 32 - Potentiometer ADC Output (Y Axis)

$$Y\ Axis\ Displacement\ = 0.2819x - 186.9\quad [\,°\,]$$

$$X\ Axis\ Displacement\ = 0.2594x - 192.9\quad [\,°\,]$$

$$Y\ Axis\ Joystick\ Position\ = 2.205x - 960.17\quad [Integer]$$

$$X\ Axis\ Joystick\ Position\ = 2.6562x - 1463.3\quad [Integer]$$

Equation 4 - Potentiometer Translation Equations

Servo Characterization

To aid in the design of a PID controller for this system the transfer function of the servos must be known. Referring to the datasheet of the Savox SA-1283SG servo it is known that the servo response time is 0.16 seconds / 60°. This specification can be rewritten in a more useful form as 375° / second. Using this information, it is assumed the servo will require 2.67ms to respond to a 1° step input. This results in a time domain unit step response as shown in Equation 5.

$$g(t) = 1 - e^{-415.697t} \ [°]$$

Equation 5 - Servo Time Domain Unit Step Response

The real-time step response of the servo is plotted in Figure 33.

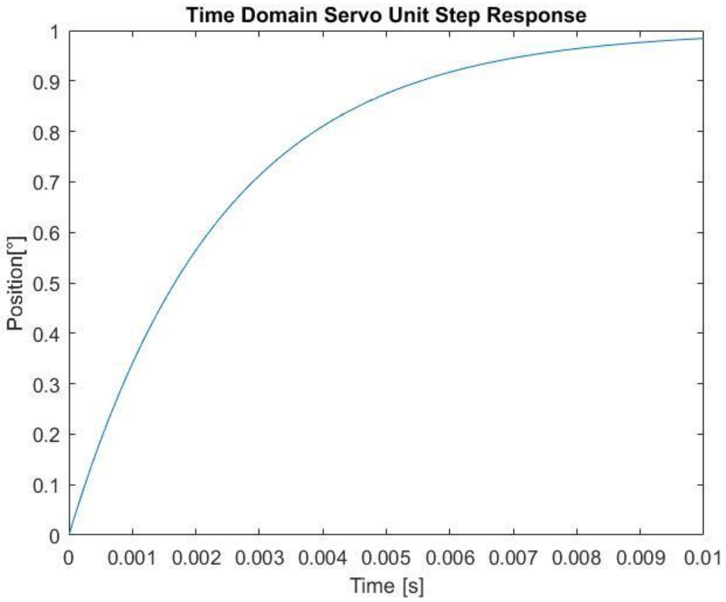


Figure 33 - Servo Time Domain Step Response

The Laplace transform of the time domain response was taken to come up with a transfer function G(s) as shown in Equation 6.

$$G(s) = \frac{415.697}{s + 415.697}$$

Equation 6 - Servo Transfer Function

Control System Tuning and Simulation

Ziegler-Nichols Tuning Method

Tuning of the experimental PID controller was accomplished using the Ziegler-Nichols method. Being that the PID control is implemented on the microcontroller, the discrete version of the Ziegler-Nichols values was required. A discrete PID controller transfer function can be represented by the following equation:

$$T(s) = K_P e[n] + K_i \sum_{k=0}^{n} e[k] + K_d(e[n] - e[n-1])$$

Equation 7 - Discrete PID Transfer Function [13]

Where K_P, K_D, K_I are obtained using a combination of the sampling, integration and derivative times. The first step in determining these constants is determining the K_P value at which an oscillation in the output is sustained. This value is referred to as K_C and the period of oscillation is P_C. Both constants are then used to determine the integration period, T_i, and derivative period, T_d, as shown in Table 5.

Controller	K_P	T_i	T_d
P	$0.5K_C$	-	-
PD	$0.65K_C$	-	$0.12P_C$
PI	$0.45K_C$	$0.85P_C$	-
PID	$0.65\ K_C$	$0.5P_C$	$0.12P_C$

Table 5 - Ziegler-Nichols Values [13]

The K_D and K_I constants can then be calculated using the following equations:

$$K_i = \frac{K_P T}{T_i} \quad K_d = \frac{K_P T_d}{T} \quad T = sample\ period$$

Equation 8 - K_i and K_d Equations [13]

The control loop implemented on the microcontroller repeats at intervals of 86ms which is the sampling period, T. The controller was modified to be P control only and K_P was increased until oscillation was sustained at which point the value was recorded as K_C. The oscillatory response is shown in Figure 34. This information was applied through the Ziegler-Nichols method to obtain the initial PID constants as shown in Table 6.

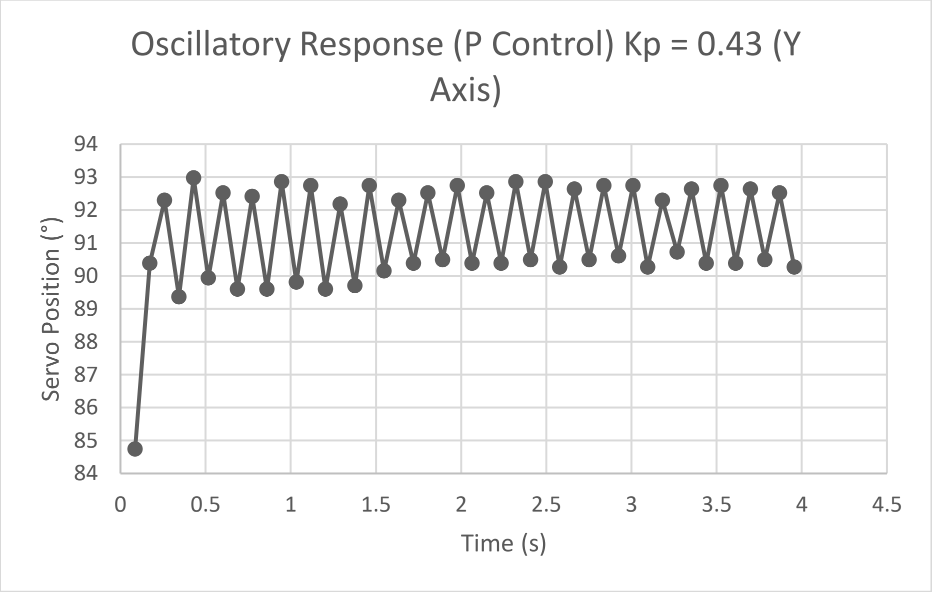


Figure 34 - Experimental Oscillatory Response

Variables	
T	0.086 (s)
K_C	0.43
P_C	0.172 (s)
T_i	0.1462 (s)
K_i	0.1138
K_P	0.1935

Table 6 – Experimentally Tuned PID Constants

After applying the new values of K_P and K_i a stable response was obtained as shown in Figure 35.

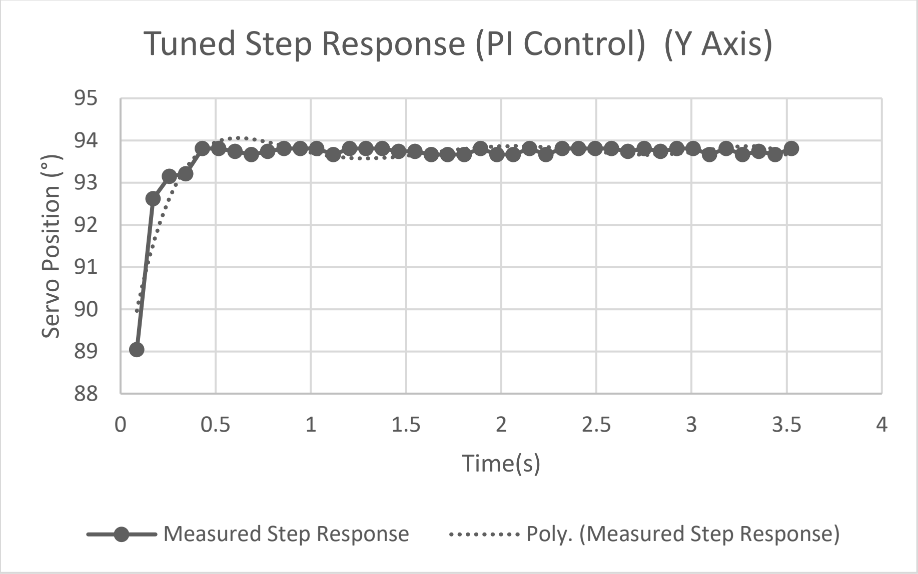


Figure 35 - Experimentally Tuned PI Step Response

Simulink System Model

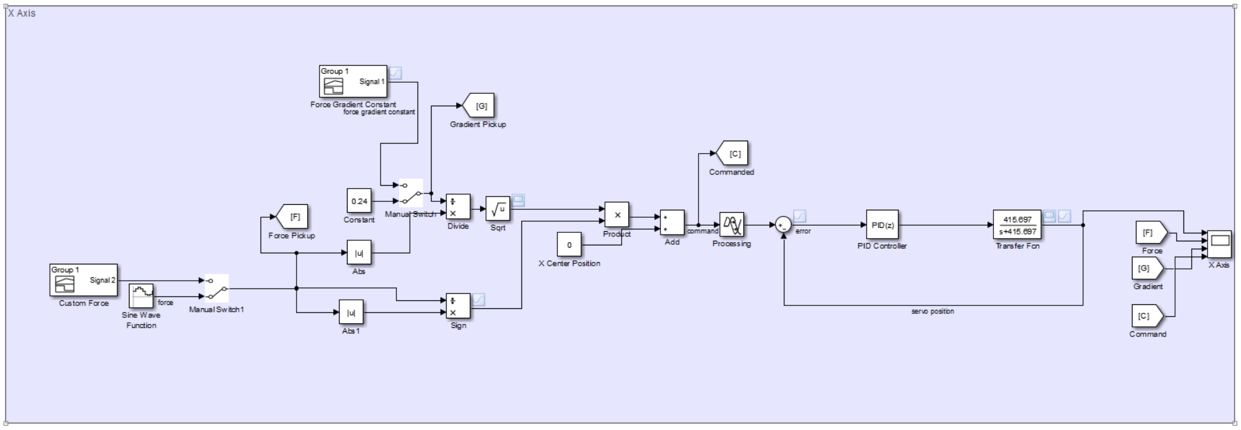


Figure 36 - Simulink Control System Model

In the Matlab simulated system, several math blocks were used to implement the force to degrees of displacement translation. A varying force is applied to the system as a discrete sine wave; this is to simulate the discrete steps in which force is sampled from the HX711 devices. The force is then translated to degrees using previously defined Equation 1 - Force and Position Relation. The resulting value, in degrees, becomes the set point for the PID controller.

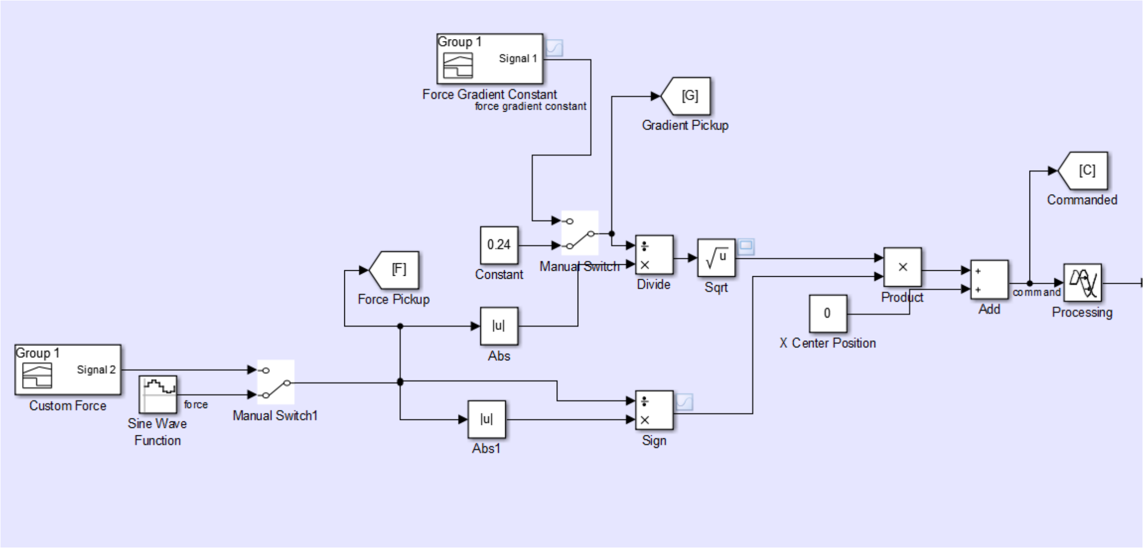


Figure 37 - Simulink Model (Part 1)

A discrete PID controller is placed in the forward path of the control system. The sampling period of 86ms from the microcontroller is used for this PID. The servo transfer function, as previously defined, is also placed in the forward path. The output is in units of degrees.

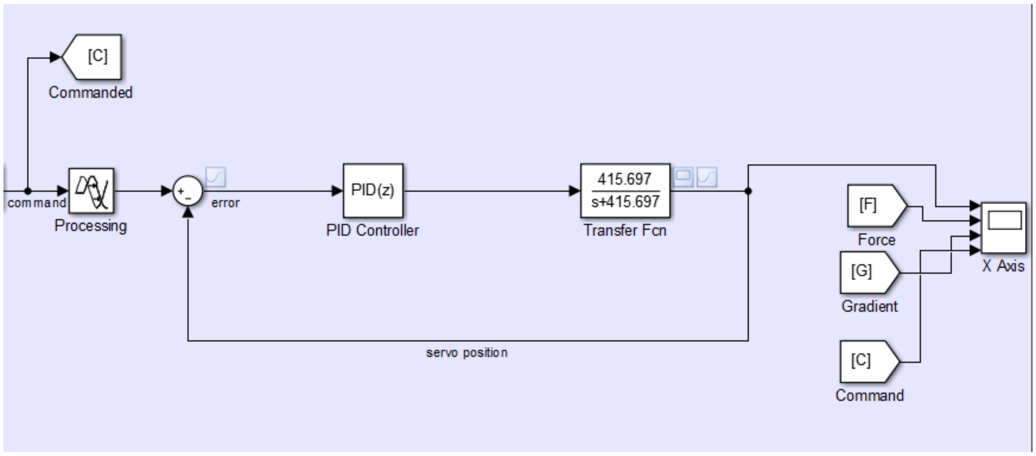


Figure 38 - Simulink Model (Part 2)

The PID block was initially given the K_P and K_i parameters discovered experimentally to observe the response as shown in Figure 39. The commanded position is in blue, and the actual servo position is in green. The response is far too slow. When using the same parameters in the actual system, the servos are more responsive.

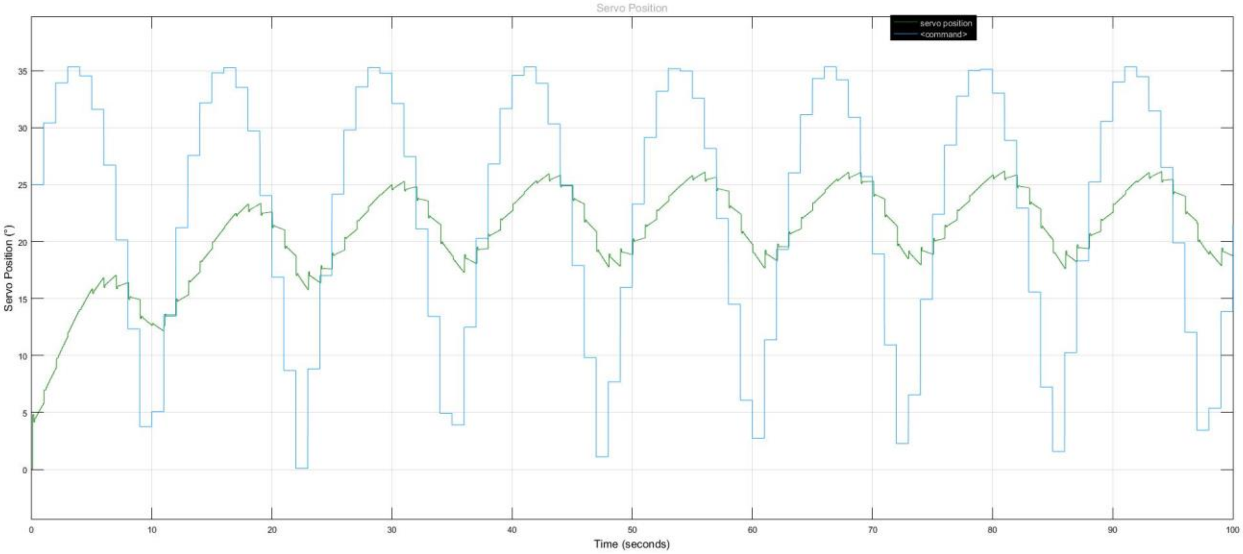


Figure 39 - Experimentally Tuned PD Simulation

Using the “Auto-tune” feature of Simulink, the following PID parameters were obtained.

Variables	
K_P	0.221
K_D	2.575

Table 7 - PID Parameters from Simulink

Running the simulation with the new K_P and K_D constants produced a more desirable result as seen in Figure 40. The servos respond faster and adjust for steady state error.

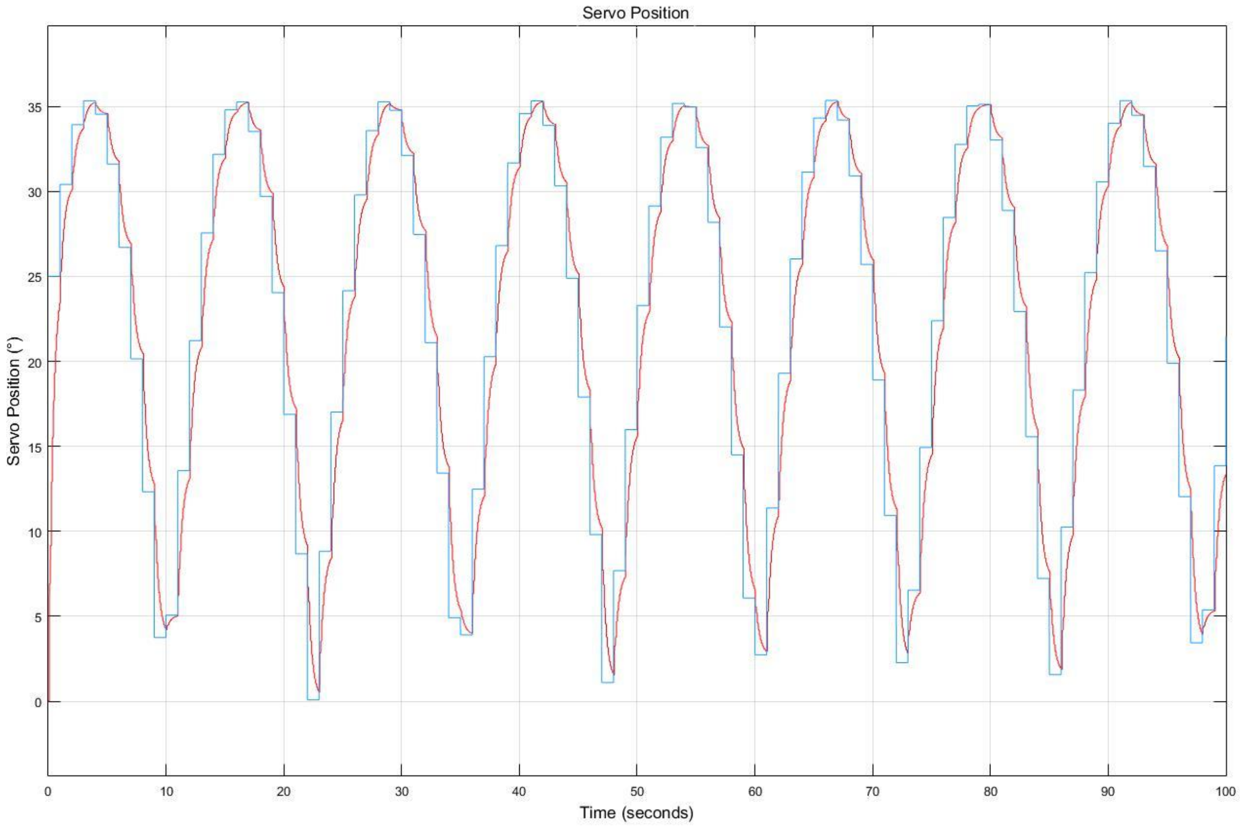


Figure 40 - Simulink Tuned PD Control Simulation

To observe the effect of a varying force gradient constant, K_G, a custom waveform that varied from 0.24 to 0.75 was applied to the system. The varying K_G could represent changing flight variables of a real aircraft. As K_G increased, it’s clear from the response that it requires more force to move the servos. Likewise, a smaller K_G means less force is required to move the servos by the same amount. Figure 41 plots the servo movement, applied force, force gradient and commanded servo position to better visualize the effect of a varying K_G. It can be seen when K_G suddenly decreases, the servo displacement increases for the same amount of force.

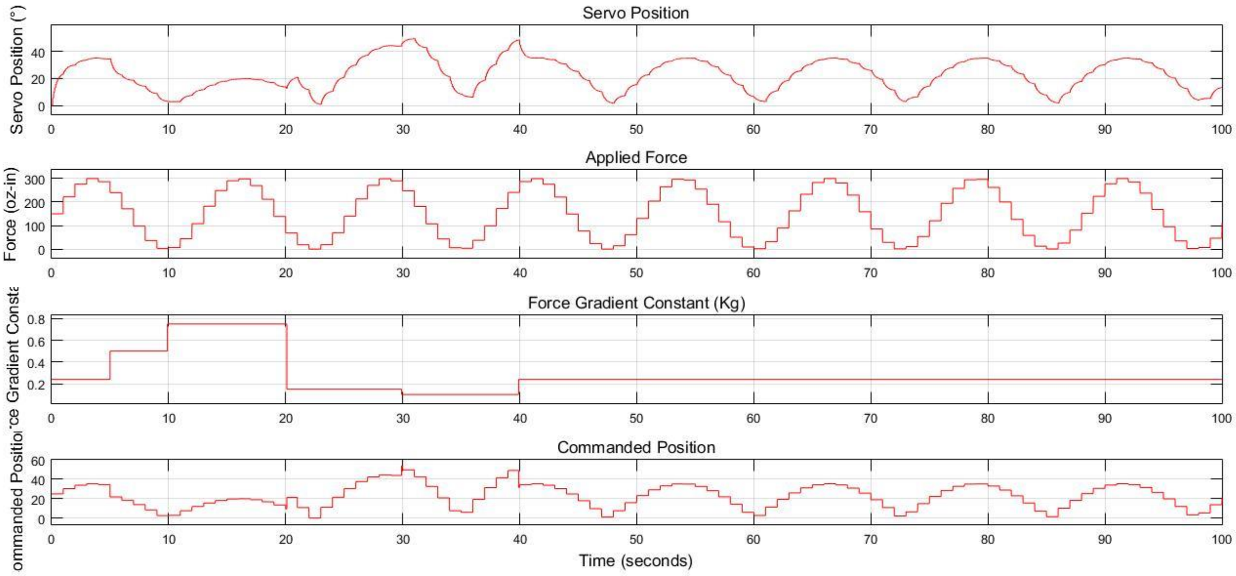


Figure 41 - Simulation of Varying Force Gradient

System Response

The PID constants determined from both the Ziegler-Nichols method and Simulink were applied to the system to determine which set performed better.

The Simulink values shown in Table 7 produced oscillations greater than the servos could handle. The K_D constant was too large. For this reason, the PID constants were reverted to the values shown in Table 6.

To test the control system a sinusoidal force was applied to the grip while reading out the commanded position, PID controller output and time. The commanded position is the value calculated using Equation 1.

The system response with the values of Table 6 is shown in Figure 42. It is obvious that the PID output significantly lags the instantaneous commanded position. While this is not the desired behavior, it is necessary for the stability of the system. Introducing larger PID constants quickly results in wild oscillations which will be seen in another figure. With K_I set at 0.1138 there is still a small steady state error visible. At maximum deflection, there is a 23 degree lag between the commanded position and PID output.Figure 42 - System Response to Sinusoidal Input (Ziegler-Nichols)

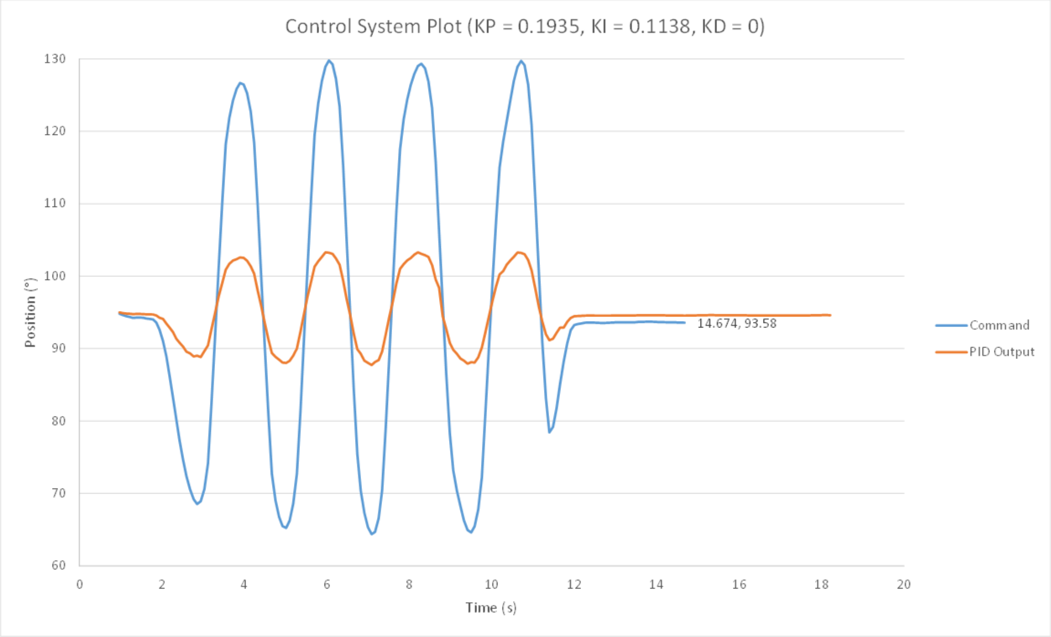


Figure 42 - System Response to Sinusoidal Input (Ziegler-Nichols)

The K_P and K_I values were adjusted further through trial and error to become 0.2 and 0.35 respectively. The new system response can be seen in Figure 43. There is still about a 17 degree lag between the commanded position and PID output but the steady state error was reduced to nearly zero.

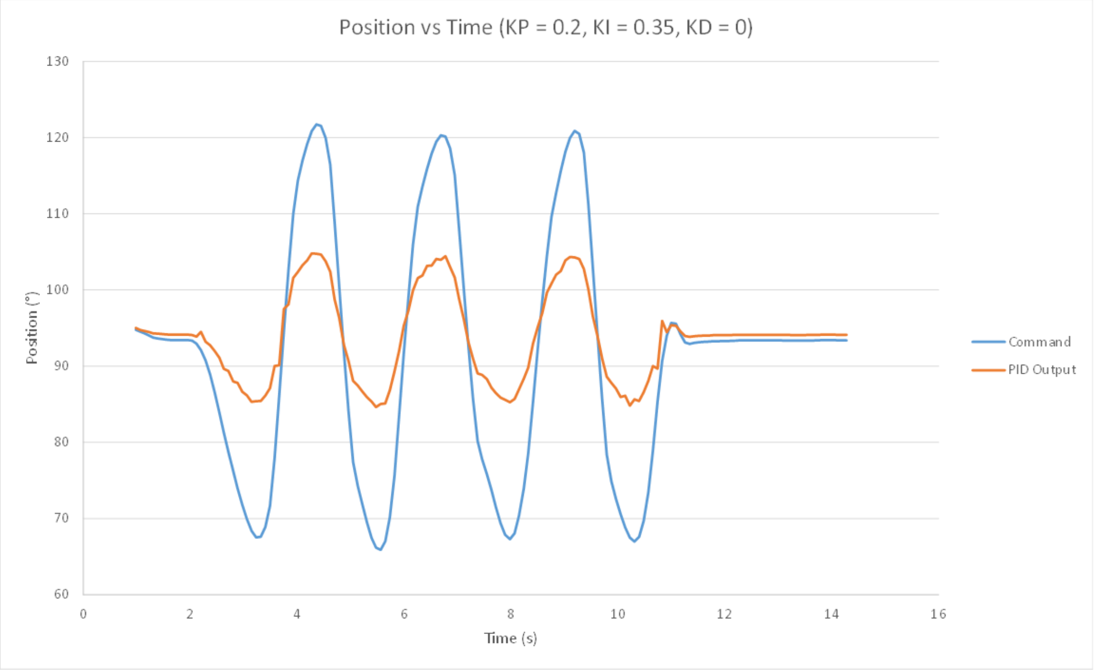


Figure 43 - System Response to Sinusoidal Input (Adjusted Z-N)

To demonstrate the instability caused by too large of a K_I or K_D constant, in the next test case the K_P and K_I constants were changed to 0.2 and 1.1 respectively. The PID output begins to oscillate at the peaks of the sinusoidal input. This oscillation can become violent enough that the servos stop responding to commands. The response can be seen in Figure 44.

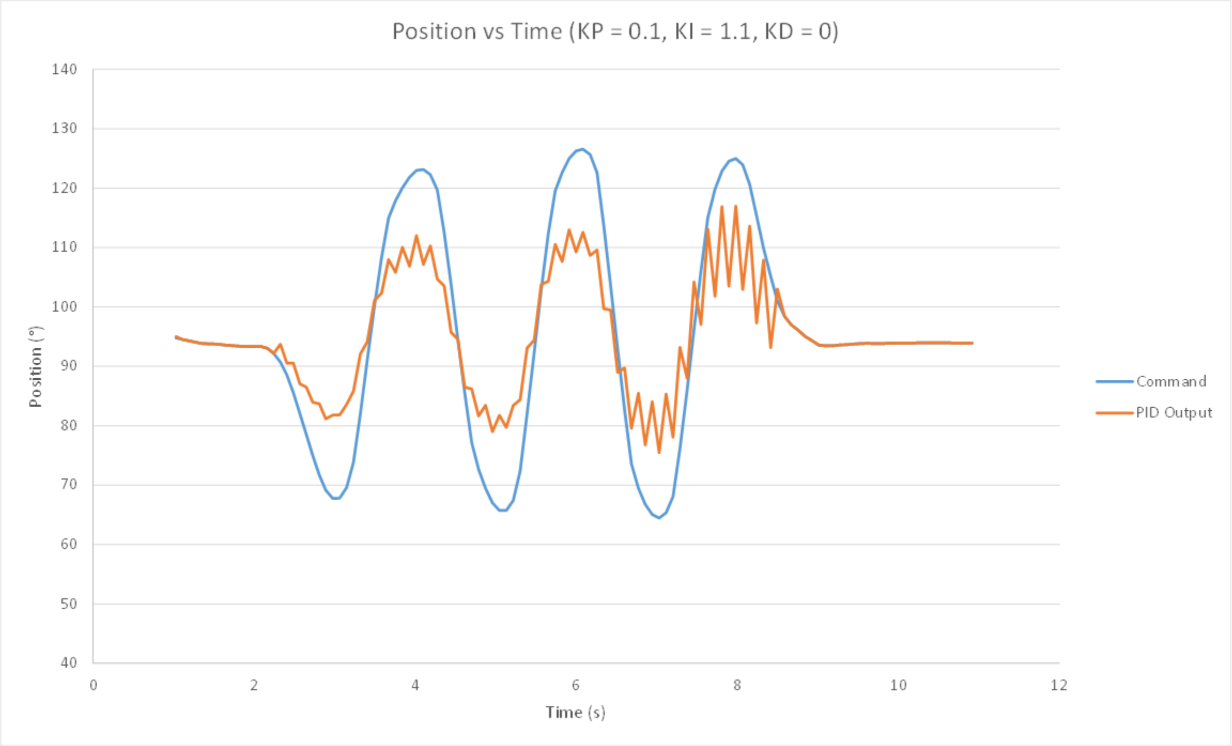


Figure 44 - System Response to Sinusoidal Input (Oscillatory)

System Testing

Force Feedback Testing

Testing was conducted to verify the force and position relationship discussed under the heading Force Feedback Concept. The testing was accomplished by reading out variables from the Arduino over serial; the variables used were potentiometer position, force and commanded position. The potentiometer position is the displacement of the axis from center in degrees. The force is calibrated to ounce-inches. The commanded position is the result from applying Equation 1.

Figure 45 shows the displacement of the X axis versus the applied force. The actual sidestick movement exceeds that of the theoretically calculated position as defined by the force and position relationship. This additional movement is largely due to the slop in the servos and non-rigidity of the 3D printed structures. The servos did not meet the holding torque specifications as listed in the datasheet. The plastic structures also were not nearly rigid enough for this application.

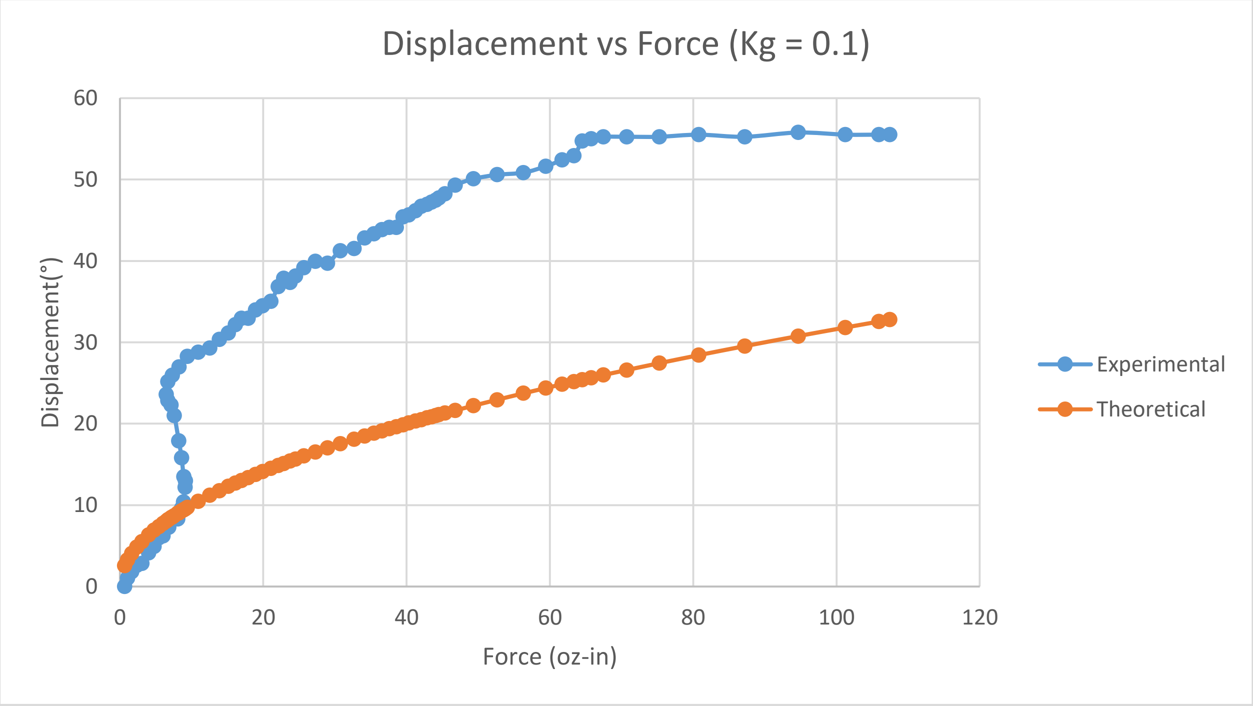


Figure 45 - Experimental and Theoretical Force and Position Relation

The next test was varying the force gradient constant to see if the force and position relationship holds. Figure 46 plots the response of three different force gradient constants. The plot proves that a lower force gradient constant results in much more displacement while a higher constant has the opposite effect.

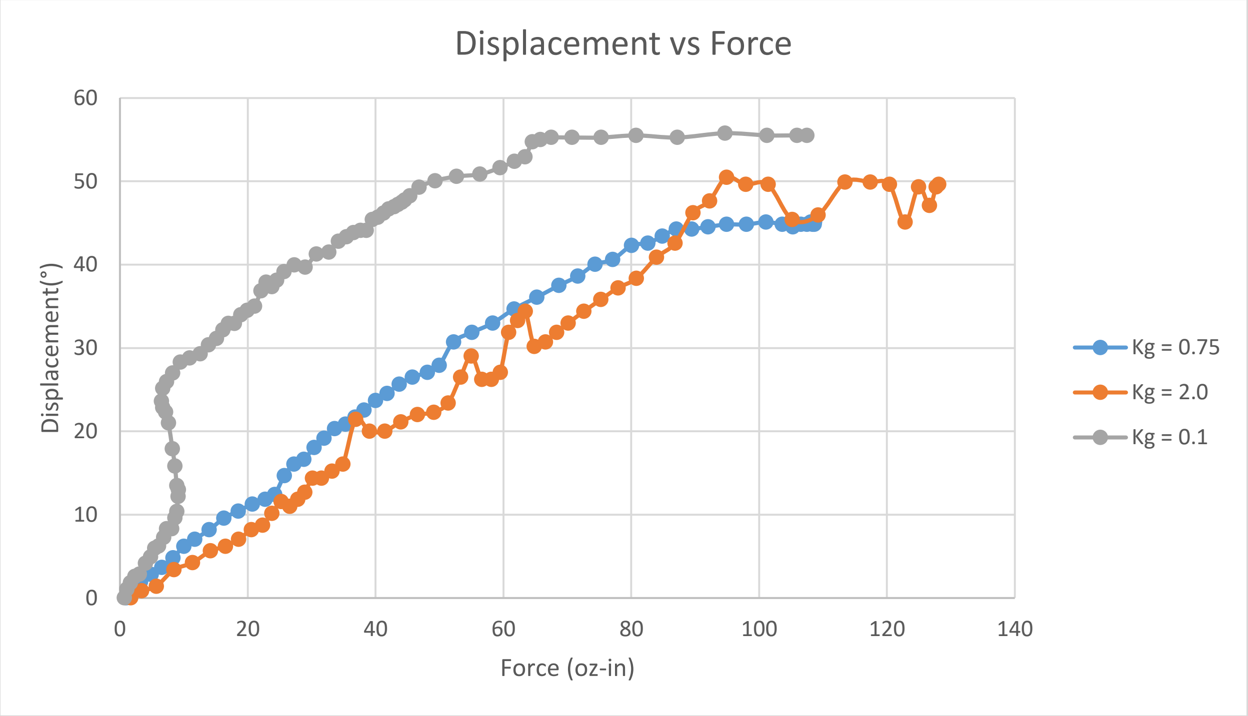


Figure 46 - Position vs Force with Varying Kg

Overall System Test and Results

The active sidestick was tested against the requirements initially set for the project. The requirement and corresponding test results are listed in Table 8.

System Requirement	Tested	Result
Varying force gradient constant based on flight conditions	Yes	Successful
The sidestick shall have standard USB interface for programming by PC	Yes	Successful
The sidestick software shall be compatible with PC flight simulators	Yes	Successful
The sidestick shall interface at least with ARINC 429 data bus topology	No	To be incorporated in later iterations.
The sidestick shall have full controllability in the event of servo or mechanical failure	Yes	Successful
The sidestick shall incorporate independent power supplies for the servos and logic devices in case of faults	Yes	Successful
The sidestick shall not exceed a rectangular form factor of size 24 x 24 x 24 inches	Yes	Successful
The sidestick shall have a grip that can be interchanged for right or left handed operation	Yes	Successful

Table 8 - System Test Results

Project Schedule

Timeline and Major Milestones

The following table presents major milestones in the project timeline. The schedule will be further broken down into a Gantt chart.

Milestone	Quarter	Date
EE 460 Final Senior Project Report Due	Fall 2016	November 28th, 2016
Design Review	Winter 2017	February 13th, 2017
Mid-project Demonstration	Winter 2017	March 13th, 2017
Final Project Demo	Spring 2017	June 14th, 2017
EE Senior Project Expo	Spring 2017	June 2nd, 2017

Table 9- Major Milestones

The project is of such complexity that it will be broken down into smaller portions for demonstration purposes. Also, due to the complexity there are several risks to the proposed project timeline that may be encountered. A few of the projected risks are:

1. Software development overhead for interaction between the hardware and connected PC
2. The complex gimbal mechanism will require machining or 3D printing and careful assembly
3. The final step of integrating the DC servos and controller could be the most time-consuming process and extend beyond the project expo date

To better identify the individual milestones and associated deliverables, a Gantt chart is provided below.

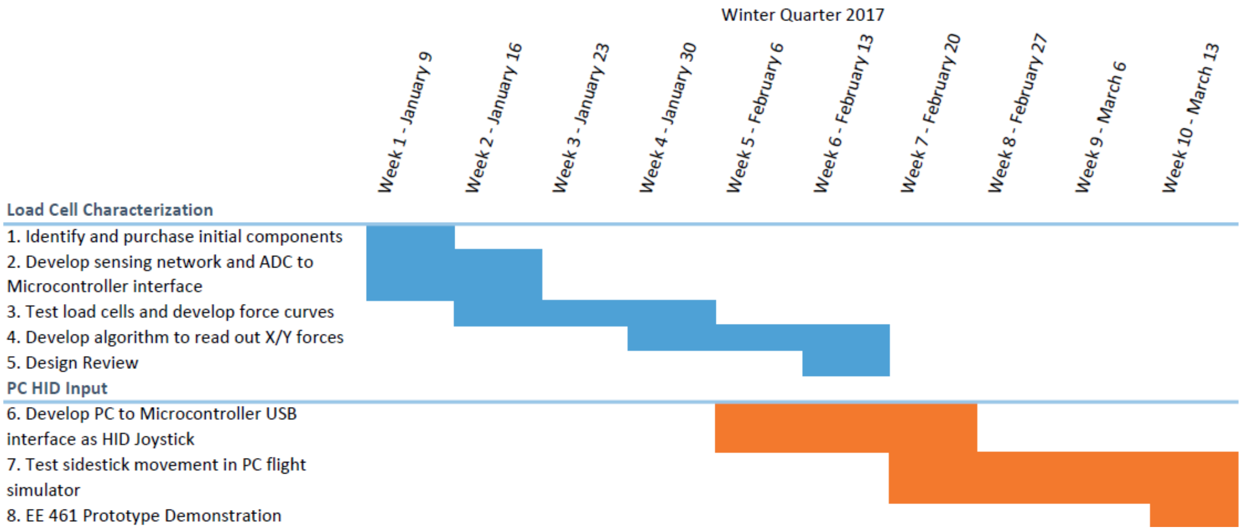


Figure 47 - Winter 2017 Schedule

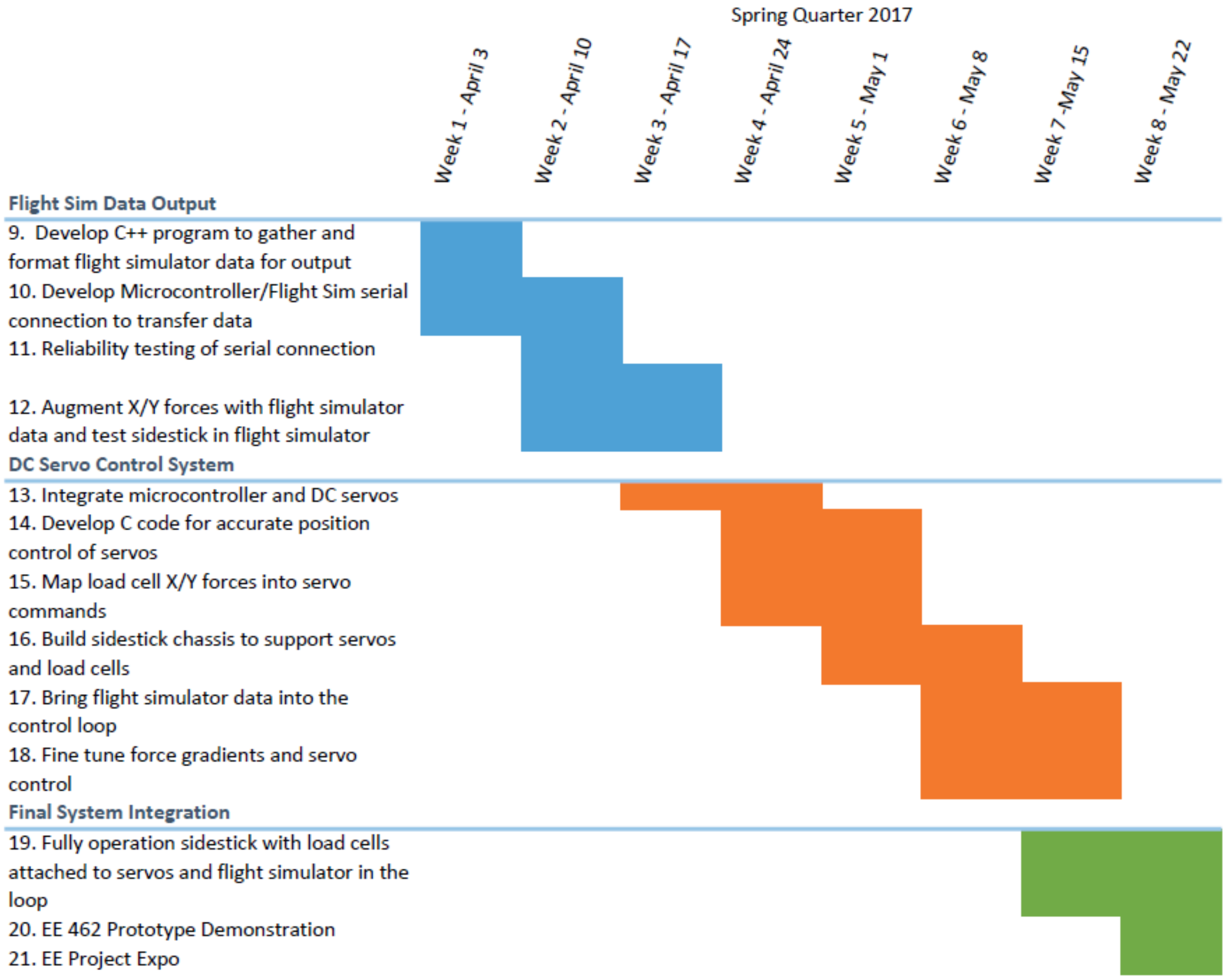


Figure 48 - Spring 2017 Schedule

Task Breakdown

The tasks shown in the Winter and Spring Gantt charts are further broken down in the following table.

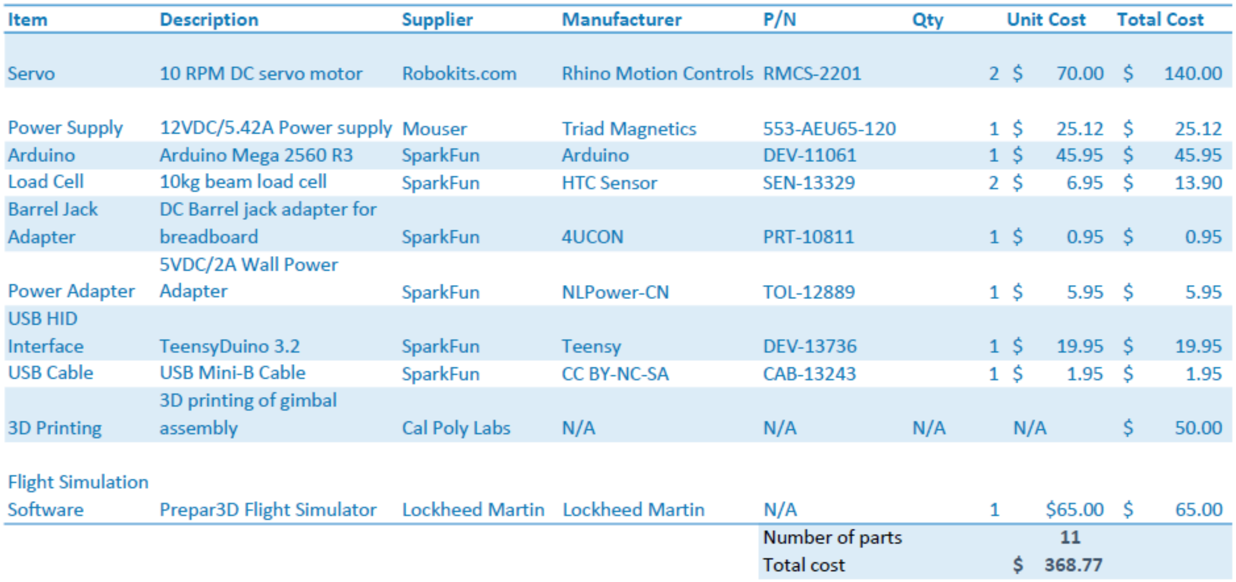
Task	Deliverables	Projected Due Date
1	○ Purchase initial components required to characterize the load cells	January 16th
2	○ Develop analog sensing interface ○ Implement analog-digital converter for use with microcontroller	January 16th
3	○ Develop load cell force curves to fully characterize the response to user input force	February 6th
4	○ Devise a linear equation to map force input to sensor output ○ Use USB debugger to continuously read out X/Y force inputs	February 13th
5	○ Design review with faculty advisor, Dr. Benson	February 13th
6	○ Write C code for microcontroller to emulate a joystick human interface device (HID) over USB	February 20th
7	○ Using the developed HID interface, test the sidestick control in the flight simulator software environment ○ Fine tune load cell calibration to provide consistent and realistic control inputs in the simulator	March 6th
8	○ Prototype demonstration for faculty advisor, Dr. Benson	March 13th
9	○ Develop GUI based C++ application to interface with the flight simulation software and gather relevant flight data	April 3rd

10	○ Implement serial data transfer between the C++ software and microcontroller ○ Microcontroller reads in flight variables and outputs current state variables	April 10th
11	○ Robustness testing of serial data link over USB while flying in the flight simulator using the sidestick as control input	April 10th
12	○ Using the flight variables provided by the flight simulator, augment the mapping of force input to X/Y control position ○ Define the effect of flight variables on the control output	April 17th
13	○ Integrate the microcontroller with the two DC servos ○ Purchase and configure DC power supply for use with the servos	April 17th
14	○ Develop C code library to allow simple position control of the DC servos ○ Test the reliability of position commands	April 24th
15	○ Devise algorithm to map X/Y control output, before flight simulator data augmentation, to DC servo position commands	April 24th
16	○ Build 3D model of gimbal mechanism and sidestick chassis ○ 3D print the model and assemble parts	May 8th
17	○ Build upon previous algorithm to augment the DC servo commands with flight simulator data	May 15th
18	○ Make final adjustments to all algorithms to ensure smoothness of DC servo control and realistic flight control responses in the simulator	May 15th

19	○ Perform final assembly of all components integrated into the sidestick chassis and gimbal	May 22nd
20	○ Final project demonstration for faculty advisor, Dr. Benson	May 22nd
21	○ EE Senior Project Expo	June 2nd

Costs and Resources

If the manufacturing of the ActivSense Sidestick were to go live funding for materials, research, design and manufacturing would be sought from industry partners and investors. Funding for the senior project will come from Cal Poly's Electrical Engineering department as well as the Autonomous Flight Lab.



Item	Description	Supplier	Manufacturer	P/N	Qty	Unit Cost	Total Cost
Servo	10 RPM DC servo motor	Robokits.com	Rhino Motion Controls	RMCS-2201	2	$ 70.00	$ 140.00
Power Supply	12VDC/5.42A Power supply	Mouser	Triad Magnetics	553-AEU65-120	1	$ 25.12	$ 25.12
Arduino	Arduino Mega 2560 R3	SparkFun	Arduino	DEV-11061	1	$ 45.95	$ 45.95
Load Cell	10kg beam load cell	SparkFun	HTC Sensor	SEN-13329	2	$ 6.95	$ 13.90
Barrel Jack Adapter	DC Barrel jack adapter for breadboard	SparkFun	4UCON	PRT-10811	1	$ 0.95	$ 0.95
Power Adapter	5VDC/2A Wall Power Adapter	SparkFun	NLPower-CN	TOL-12889	1	$ 5.95	$ 5.95
USB HID Interface	TeensyDuino 3.2	SparkFun	Teensy	DEV-13736	1	$ 19.95	$ 19.95
USB Cable	USB Mini-B Cable	SparkFun	CC BY-NC-SA	CAB-13243	1	$ 1.95	$ 1.95
3D Printing	3D printing of gimbal assembly	Cal Poly Labs	N/A	N/A	N/A	N/A	$ 50.00
Flight Simulation Software	Prepar3D Flight Simulator	Lockheed Martin	Lockheed Martin	N/A	1	$65.00	$ 65.00
				Number of parts		11	
				Total cost		$ 368.77	

Table 10 - Bill of Materials

Required Skills

Successful completion of this project will require skills in all areas of electrical engineering as well as a deeper understanding of C/C++ software development. Sensing, analyzing and converting the load cell signals to the digital domain will require a mix of analog and digital electronics. The force feedback and DC servo loop will also require heavy use of control system theory. Communications between the flight simulation software and the sidestick will require extensive programming to define a protocol that converts the flight simulator program data into something useable by the sidestick microcontroller.

Conclusion and Future Improvements

Many different design choices would have been made if greater funding was available for this project. Aerospace products are inherently more expensive than other industries due to the higher quality of materials and additional design and testing that goes into any given product.

Given the limitations of a project with very little funding the sidestick was successful as a proof of concept.

Mechanical Assemblies

One of the most limiting components of the design is the gimbal mechanism. Having a complex structure, it was most cost effective to manufacture it through 3D printing with standard ABS plastic. The plastic had very poor rigidity which allowed the structure to flex when force was applied to the stick. A future design would be made such that it could be machined out of aluminum or similar metals using CNC machine processes.

Servo

The use of a high torque RC servo is not viable for a production product at all; it was chosen primarily due to the cost limitations. The servo was found to have virtually zero holding torque when it is in the process of moving to a new position. This is a problem for this design as the servos are almost always adjusting position to match user input to the stick. They also did not hold up to the rated torque. Future iterations would make use of electric hydraulic or DC worm gear servos. A worm gear motor would provide enough holding torque to prevent any damage to the DC motor; it would also reduce the wear and tear on the motor caused by locked rotor conditions.

Load Cell

The SMD M200 load cell had excellent accuracy when it comes to providing consistent, calibrated force readings. The maximum torque rating was not sufficient for this application which likely caused greater hysteresis over its period of use in this project. The best approach would be incorporating strain gauges directly into the stem of the sidestick grip; this was not the best approach for this project due to the precision required to correctly mount the strain gauges. The 30 gauge leads on the load cell were very brittle and had to be soldered back on after breaking off with the slightest movement.

Microcontroller

The primary limitation related to the microcontroller is the speed at which the control algorithm, to include the PID controller, could be run. The MCU was required to read both analog and digital data from the potentiometers and HX711 devices respectively. This processing added to the overall time required to complete one loop. Communication between the MCU and flight simulation PC also held up the control loop whenever data was sent or received. An MCU capable of threading would be a better fit for future iterations. An FPGA running multiple state machines simultaneously would also be a possibility.

Additional Software

As the project advances the communication between the active sidestick and flight simulation PC should be optimized. A standard message format should be defined to allow expansion for future data types not thought of at this point. Ideally the active sidestick would communicate using one of the standard ARINC protocols as described under Avionics Backward Compatibility.

Analysis of Senior Project

Summary of Functional Requirements

The ActivSense Sidestick will transform user force input into flight control outputs. The sidestick will be able to operate in manual mode which linearly maps force input to flight controls. During full operation, the sidestick will interpret flight variables and adjust the flight control output in a well-defined manner. End users will be able to modify the force gradients to accommodate any type of aircraft.

Primary Constraints

The primary constraint and challenge of this project will be the integration of the DC servo motors. Due to the number of variables present during aircraft flight a control system could be another project itself alone. The servo control system is expected to span 50% of the project development timeline. Building the chassis will require parts in complex shapes that need to be machined or 3D printed. Final assembly of the sidestick chassis with working servo motors will come in the last days of the project timeline.

Economic Impact

Human Capital

Just in consideration of the development cycle of the sidestick product hundreds of jobs will be either supported or created. The primary source of employment will occur in the machining and manufacturing phase of the development and final product roll out. Engineering will account for the smallest percentage of the supported workforce. Beyond manufacturing of the product itself, the manufacturers of individual components used in the design will also employ hundreds of workers. With several components sourced outside of the United States, many countries will benefit from the production.

Financial Capital

The sidestick is designed to target smaller businesses, as well as the large defense companies, that would normally not be able to afford active sidestick technology. The sidestick could result in weight savings in many types of aircraft which would also save manufacturers money over a longer period. Introducing a viable sidestick alternative in the market will also promote competition in the industry and ultimately reduce the cost of the technology while making it available to all businesses.

Natural Capital

The sidestick will be manufactured using many different types of materials. The chassis may first be built using hardened plastic while a final product would be built of more durable material such as aluminum. Individual electronic components will be carefully chosen to include only RoHS compliant devices. At the end of life, the sidestick will most likely be recycled in the same facility that processes retired aircraft. Training will be provided by the company to ensure all components of the sidestick are properly recycled.

Costs and Timing

The market price of the product is expected to compete with current alternatives available. There are no prices listed on the competitor websites but it can be estimated based on the aircraft that currently make use of the active sidestick technology. An example would be the Gulfstream G500 which is priced at over $75M. It is reasonable to expect the competition to price the sidesticks around $30-40k per unit. The final version of the ActivSense sidestick will include aerospace grade materials and be subject to intense testing to meet FAA standards. Without a thorough understanding of the materials and testing involved it is difficult to estimate the final price of the product. The goal is to keep the price to the customer below $15,000. A prototype cost estimate is provided in the previous section titled *Costs and Resources*.

Manufacturability

If manufactured on a commercial basis:

a. An estimated 10-15 units will be sold in the first year.
b. The total cost of the prototype is roughly $369 as detailed in the *Costs and Resources* section.
c. Final manufacturing and testing expenses will increase the market price exponentially to about $15,000.
d. Estimated annual profit of $180,000
e. The operational costs for the end user will be primarily in annual inspections and software updates. Mechanical failures should not occur within the lifetime of the

airframe. Lifetime software updates are expected to be included with the purchase of a sidestick unit. Annual maintenance costs shall not exceed $500.

Environmental Impact

a. What environment impacts are associated with manufacturing or use of the sidestick?

The primary environmental impact will stem from the sourcing of electronics and aerospace grade materials. The various alloys used to manufacture the sidestick chassis will inevitably be sourced from mines in multiple countries. The impact of electronic material will be minimized by the strict use of RoHS compliant electronics.

b. Which natural resources and ecosystem services does the project use (directly and indirectly) improve or harm?

The most significant resources being used in the production of the sidestick are aluminum alloys. The aluminum will most likely be derived from bauxite ore which is the main source of aluminum for the world. Australia is the top producer of bauxite followed by China, Brazil, India and Guinea. To reduce the impact of the sidestick production and use on the environment a recycling program will be established. Proper disposal and recycling of the aluminum parts, as well as electronics, will aid in reducing the electric power required to produce aluminum.

c. How does the project impact other species?

The sidestick will be produced in the most efficient and environmentally conscious method possible but there is still the chance other species will be impacted. It is possible that the use of the sidestick will indirectly affect other species based on what operations the sidestick might support (Aerial strikes by drones, agricultural pesticide spraying aircraft, etc).

Sustainability

a. Describe any issues or challenges associated with maintaining the completed device.

   The most significant challenge will be continued software updates for all of the sidesticks still in use. As the customer base grows, software maintenance will become the business's largest overhead. Backwards compatibility when new versions are released will also be important to the sustained operations.

b. Describe how the product impacts the sustainable use of resources.

   As described in previous sections, a recycling initiative will be set in place from the beginning of the lifecycle. To increase overall sustainability, strict recycling procedures of the metal and electronic components must be adhered to.

c. Describe any upgrades that would improve the design of the project.

   An upgraded gimbal and chassis would reduce the overall size of the sidestick and allow it to be used in many more applications. Mechanical expertise shall be sought to continually improve the design by reducing the physical footprint.

d. Describe any issues or challenges associated with upgrading the design.

   Most of the issues associated with upgrading the design would come in the form of backwards compatibility with sidesticks already in use. Customers may feel entitled to a free upgrade if new designs are released often. Care shall be taken to ensure each design release encompasses enough changes to warrant the purchase of a new sidestick rather than upgrading.

Ethical Implications

Briefly touched upon in previous sections, there are several ethical implications from the production of the sidestick. The sidestick is being marketed almost exclusively for the aerospace industry which means that it can end up supporting any number of aerial activities. Sidesticks being used in the operation of military drones that carry out ballistic airstrikes is just one example of ethical conflict.

Health and Safety

The safety of end users is of paramount importance in the design of the sidestick. Increased safety is the primary reason the sidestick is being developed to begin with. Safety of pilots and passengers are expected to increase dramatically as the product is phased into commercial and military aircraft. Health impacts will be minimal if not completely non-existent; the users will be in direct contact with the plastics which will be thoroughly researched for any possible adverse health effects.

Social and Political Implications

a. Social and political issues associated with design, manufacture and use.

   Similar to the ethical implications, depending on the use of the sidestick there are many social and political issues that could arise. International trade and relations are at the highest tensions with the current problems faced in the Middle East. Use of the sidestick in support of military activities could have significant political impacts as well as unforeseen social implications.

b. Who does the project impact? Who are the direct and indirect stakeholders? How are they affected?

   The sidestick has a far-reaching impact in consideration of the numerous direct and indirect stakeholders. Citizens of the countries that employ use of the sidestick in military operations will be indirect stakeholders of the sidestick. In the commercial market, passengers of airlines will also be direct stakeholders based on their desire for increased safety in aircraft operations.

Appendix

Schematics

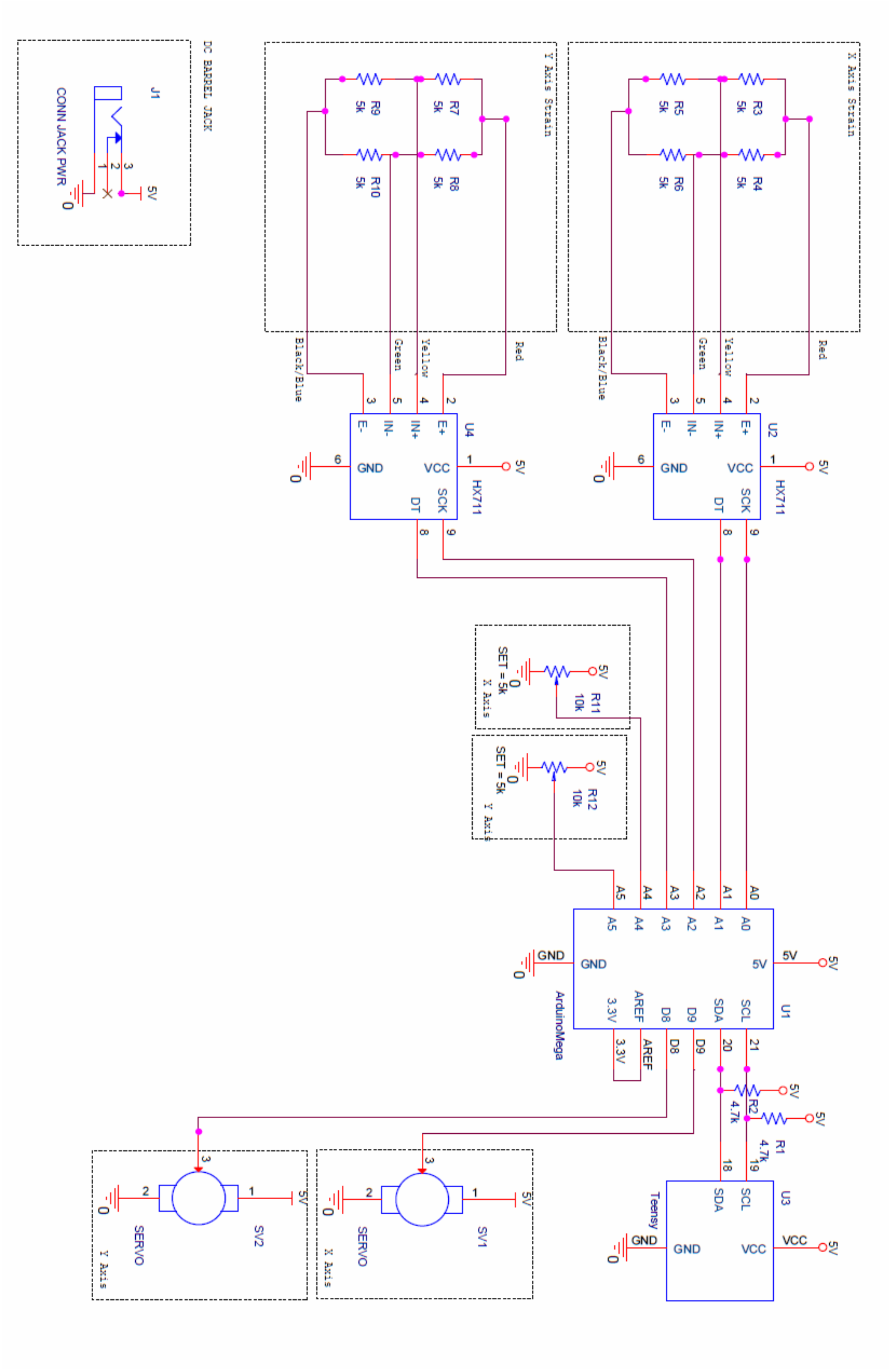


Figure 49 - Main Schematic

Code

```
#include "HX711.h"
#include <Wire.h>
#include <Servo.h>
#include "PIDuino.h"

//  HX711.DOUT  - pin #A1
//  HX711.PD_SCK    - pin #A0
//  HX711.DOUT - pin #A3
//  HX711.PD_SCK - pin #A2
//  Arduino SCL = 21
//  Arduino SDA = 20
//  Teensy SCL = Pin 19
//  Teensy SDA = Pin 18
//  X Axis Potentiometer = A4
//  Y Axis potentiometer = A5
//  write(25) -> 200 ( 0 deg -> 160 deg)
//  writemicro(1000) -> 4000 uS = 0 deg -> 160 deg

String incomingString[3] = "";    // string to hold incoming serial
unsigned long prevTime;           // Holds previous time in milliseconds
unsigned long HZ60 = 16;          // 60 Hz interval time in milliseconds
float alt, kohls, tas;            // Floats to hold incoming data
bool newData = true;              // Serial data updated?
float scale_xpos,                 // Raw x value from HX711
      scale_ypos,                 // Raw y value from HX711
      xavg,                       // Average x value from HX711
      yavg;                       // Average y value from HX711
float xpos[5] = {0};              // Float array to hold previous x values
float ypos[5] = {0};              // Float array to hold previous y values
float x_cmd_avg[5] = {95,95,95,95,95};
float y_cmd_avg[5] = {100,100,100,100,100};
int    sample = 0;                // Sample number for averaging
int    x_ozin_scale = 24520;      // Scaling factor to produce oz-in values from HX711
int    y_ozin_scale = 24520;      // Scaling factor to produce oz-in values from HX711
int    x_pot_value,               // Raw X pot value from ADC
      y_pot_value;                // Raw Y pot value from ADC
double   x_pos_deg,
      y_pos_deg;                  // Y pot value converted to degrees of displacement
int    x_pot_scale = 1;           // Scaling factor to produce degrees for X axis
int    y_pot_scale = 1;           // Scaling factor to produce degrees for Y axis
double kp = 0.3;
double kd = 1;
double ki = 0;
double x_cmd,y_cmd;
double x_kg = 0.24;               //Force gradient constant
double y_kg = 0.24;
double x_request;
double x_averaged;
double y_request;
double y_averaged;
```

```
/* CLASSES  */

HX711 scale_y(A1, A0);      // Instantiate HX711 classes
HX711 scale_x(A3, A2);      // parameter "gain" is ommited
Servo x_servo, y_servo;
PID y_pid(0.34,0.1,0);
PID x_pid(0.02,.20,0);
/* PINS  */

int x_pot_pin = A4;        //Connect X pot to A4
int y_pot_pin = A5;        //Connect Y pot to A5

/* FUNCTION DECLARATIONS  */

void float_to_bytes(float data);
void retrieveData(float* alt, float* kohls, float* tas);
void sendFloat(float f, float g);

/* SETUP  */

void setup() {
  Serial.begin(9600);
  pinMode(A4, INPUT);
  pinMode(A5, INPUT);
  x_servo.attach(9);          // attaches the servo on pin 2 to the x axis servo object
  y_servo.attach(8);          // attaches the servo on pin 2 to the x axis servo object
  scale_x.tare(5);            // reset the scale to 0
  scale_y.tare(5);            // reset the scale to 0
  Wire.begin();               // Begin I2C communication with Teensy
  x_servo.write(95);          //Center servo to begin
  y_servo.write(95);          //Center servo to begin
  delay(10);
}

/* LOOP  */

void loop() {

  analogReference(EXTERNAL);
  unsigned long currentTime = millis();                  //Grab current time
  x_pot_value = analogRead(x_pot_pin)/x_pot_scale;      //Grab current X pot value
  y_pot_value = analogRead(y_pot_pin)/y_pot_scale;      //Grab current Y pot value
  x_pos_deg = (x_pot_value*0.2594-207)+95;
  y_pos_deg = 100-(y_pot_value*0.2819-186.9);              //(inverted to match
  scale_xpos = scale_x.get_value()/x_ozin_scale;  //Grab raw X value and scale to oz-in
  scale_ypos = scale_y.get_value()/y_ozin_scale;  //Grab raw Y value and scale to oz-in
  xpos[sample] = scale_xpos;                      //Store X value for averaging
  ypos[sample] = scale_ypos;                      //Store Y value for averaging
  Wire.beginTransmission(0x20);                           //Open comms with Teensy (#8)
  xavg = (xpos[4]+xpos[3]+xpos[2]+xpos[1]+xpos[0])/5;       //Average X values
  yavg = (ypos[4]+ypos[3]+ypos[2]+ypos[1]+ypos[0])/5;
```

```
  if (xpos[4] == 0);  //wait until first complete average populates
  else
  {
    if (xavg < 0)
    {
      x_request = 95 - sqrt(abs(xavg)/x_kg);
      x_cmd_avg[sample] = x_request;
      x_averaged = (x_cmd_avg[4]+x_cmd_avg[3]+x_cmd_avg[2]+x_cmd_avg[1]+x_cmd_avg[0])/5;
    }
    else
    {
      x_request = 95 + sqrt(abs(xavg)/x_kg);
      x_cmd_avg[sample] = x_request;
      x_averaged = (x_cmd_avg[4]+x_cmd_avg[3]+x_cmd_avg[2]+x_cmd_avg[1]+x_cmd_avg[0])/5;
    }
     x_pid.Calculate(x_pos_deg,&x_cmd,x_averaged);
     Serial.println();
     Serial.println(-x_cmd+95);
     Serial.println();
     x_servo.write(-x_cmd+95);

    if (yavg < 0)
    {
      y_request = 100 - sqrt(abs(yavg)/y_kg);
      y_cmd_avg[sample] = y_request;
      y_averaged = (y_cmd_avg[4]+y_cmd_avg[3]+y_cmd_avg[2]+y_cmd_avg[1]+y_cmd_avg[0])/5;

    }
    else
    {
      y_request = 100 + sqrt(abs(yavg)/y_kg);
      y_cmd_avg[sample] = y_request;
      y_averaged = (y_cmd_avg[4]+y_cmd_avg[3]+y_cmd_avg[2]+y_cmd_avg[1]+y_cmd_avg[0])/5;
    }
     y_pid.Calculate(y_pos_deg,&y_cmd,y_averaged);
  }


  float_to_bytes(x_pot_value);
  float_to_bytes(y_pot_value);
  Wire.endTransmission();

  if (Serial.available() != 0)
  {
    retrieveData(&alt,&kohls,&tas);
    Serial.flush();
  }

  if (sample == 4)                              //Increment sample number for averaging
  {
    sample = 0;
  }
  else
  {
    sample++;
  }
```

```
}

/* FUNCTION DEFINITIONS  */

/*  Function:     float_to_bytes
    Description:  Breaks a float into bytes and transmits over I2C
    Inputs:       float data
*/
void float_to_bytes(float data){

  unsigned int i = 0;
  for(i=0; i<4; i++)
  {
     Wire.write( *((unsigned char*)&data + i));
  }

}


/*  Function:     retrieveData
    Description:  Grabs incoming serial data from the PC and stores it
    Inputs:       float alt, kohls, tas
*/
void retrieveData(float* alt, float* kohls, float* tas){
  int count = 0;
  while (Serial.available() > 0) {
    int inChar = Serial.read();
    if (inChar != '\n')
    {
      incomingString[count] += (char)inChar;
    }
    else
    {
      //const char *buf = incomingString[count].c_str();
      switch (count)
      {
        case 0:
          *alt = incomingString[count].toFloat();
          break;
        case 1:
          *kohls = incomingString[count].toFloat();
          break;
        case 2:
          *tas = incomingString[count].toFloat();
          break;
        default:
          *alt = incomingString[0].toFloat();
          break;
      }
      count++;
    }
  }
}

/*  Function:     sendFloat
    Description:  Sends two floats back to the PC over serial
```

```
    Inputs:       float f, g
*/
void sendFloat(float f, float g){
  byte * b = (byte *) &f;
  byte * c = (byte *) &g;
  Serial.print("f:");
  //Serial.write(b,4);
  Serial.write(b[0]);
  Serial.write(b[1]);
  Serial.write(b[2]);
  Serial.write(b[3]);
  Serial.write(c[0]);
  Serial.write(c[1]);
  Serial.write(c[2]);
  Serial.write(c[3]);
  Serial.print(68); //Send nonsense.. Else serial drops offline
  Serial.flush();
  return;
}
```

```
#if ARDUINO >= 100
  #include "Arduino.h"
#else
  #include "WProgram.h"
#endif

#include <PIDuino.h>


PID::PID(double Kp, double Ki, double Kd)
{

    kp = Kp;
    kd = Kd;
    ki = Ki;
    time[0] = 0;
    cum_err = 0;


}

 bool PID::Calculate(double feedback, double* output, double command)
 {
     PIDout = output;
     PIDfeedback = feedback;
     PIDcmd = command;
     err_sig[1] = PIDcmd - PIDfeedback;
     time[0] = time[1]; //Save previous time
     time[1] = micros();
     if (time[0] == 0) //Have we not filled the time array?
     {
         return false;
     }
```

```
      PID::Derivative();
      PID::Proportional();
      PID::Integral();

      *PIDout = P + I + D;
      err_sig[0] = err_sig[1]; //Save error signal


  }

bool PID::Derivative()
{

   double deriv = ( (err_sig[1] - err_sig[0]) );// / ((time[1] -
time[0])/1000000) );

    D = kd * deriv;
}

bool PID::Proportional()
{

    double prop = ( PIDcmd - PIDfeedback );
    P = prop*kp;


}

bool PID::Integral()
{
    double integ = ( (err_sig[1] - err_sig[0]) );//*((time[1]-
time[0])/1000000) );
    cum_err += integ;
    I = ki*cum_err;


}

void PID::SetTunings(double Kp, double Ki, double Kd)
{

   kp = Kp;
   ki = Ki;
   kd = Kd;

}
```

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