ActivSense Sidestick

A Force Sensing and Force Feedback Joystick

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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.

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 as a result 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 in order 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.

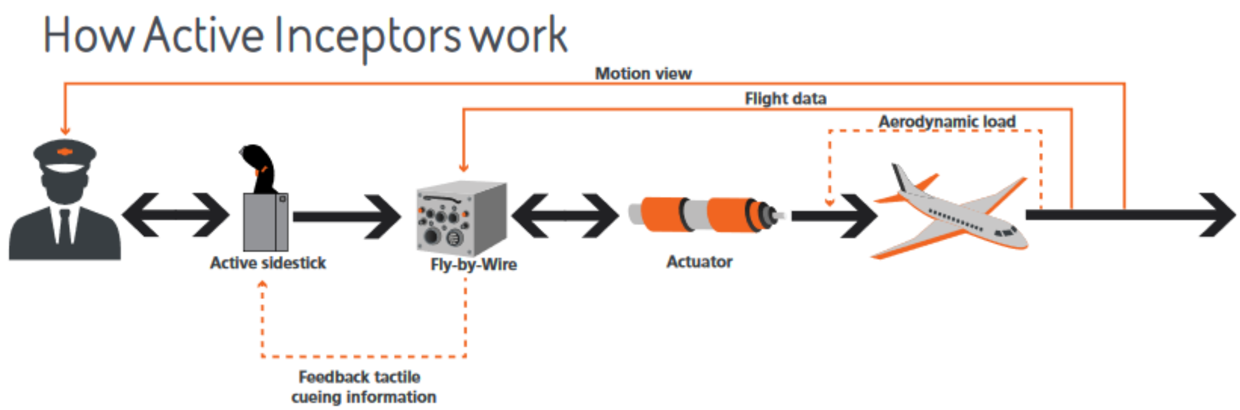


Figure 1- BAE Systems Active Inceptor Diagram [4]

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.

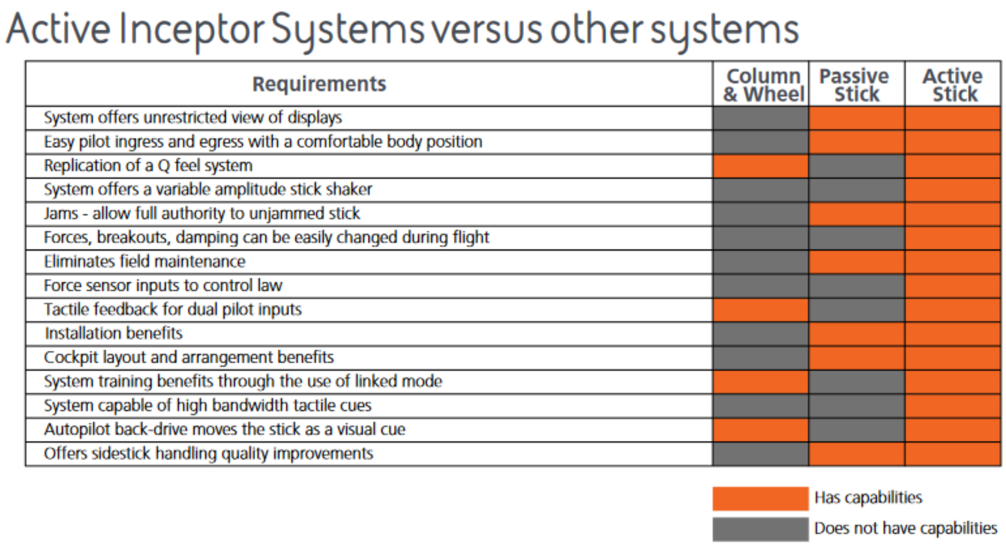


Figure 2- Active Inceptor Advantages [4]

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 in size. 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 number of avenues into the defense industry to be considered. While the active sidestick technology is not a new concept in military aircraft the majority of 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.

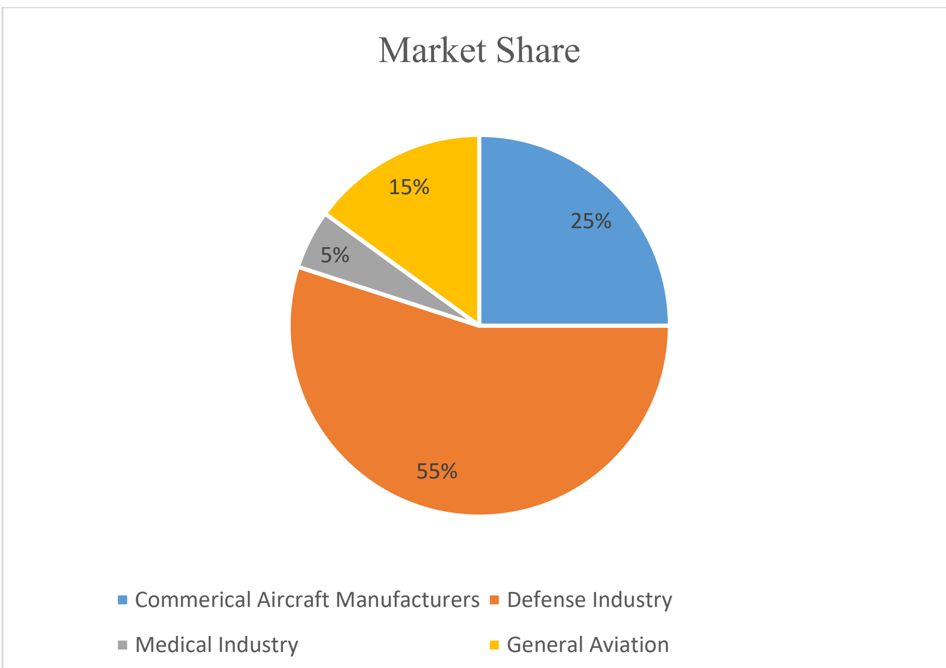


Figure 3- Market Share Pie Chart

Business Model Canvas

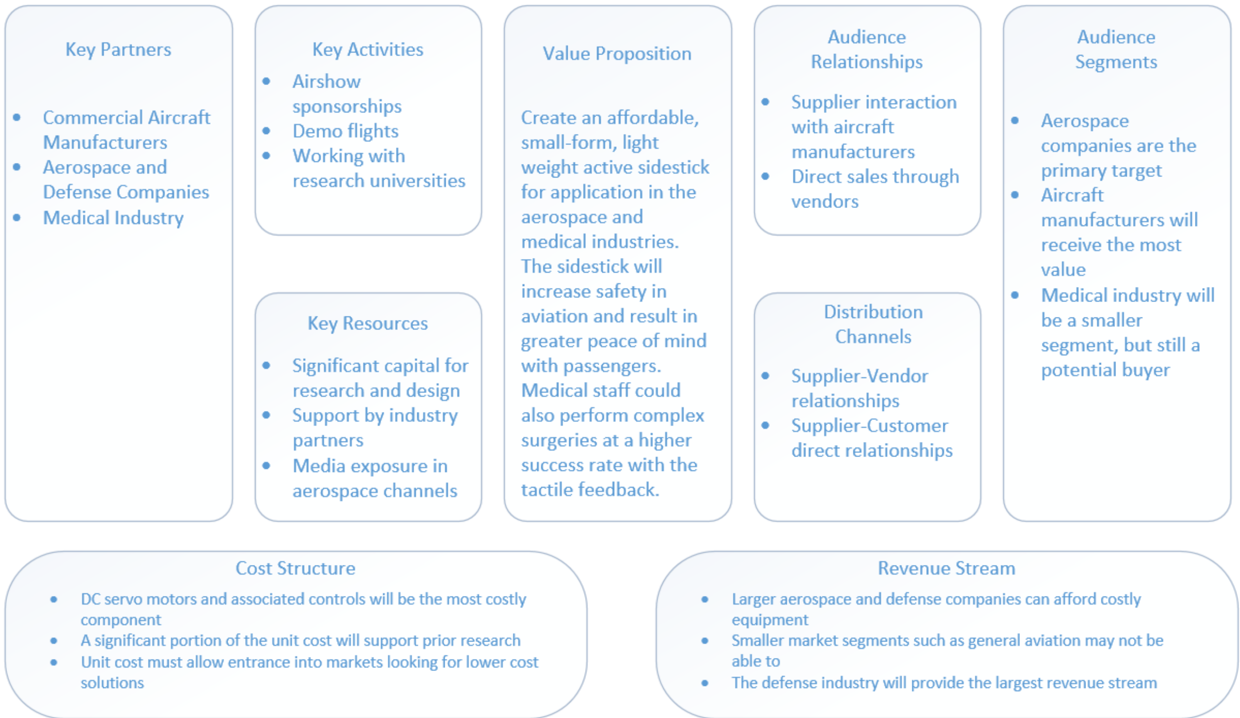


Figure 4- Business Model Canvas

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 to the fullest extent	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 through the use of 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.

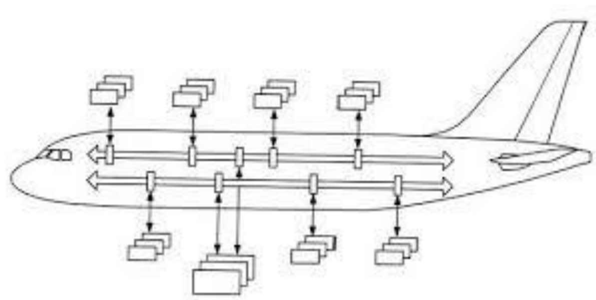
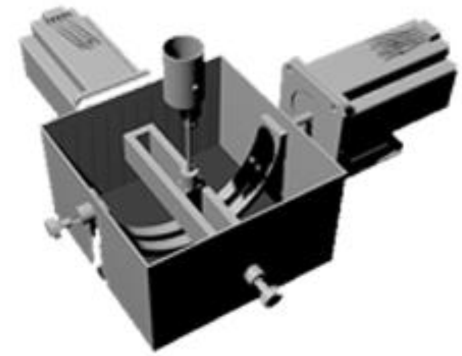


Figure 5- ARINC 429 Bus Topology

ARINC 664 is more complex protocol that is similar to 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 have the ability to interface with both of these 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

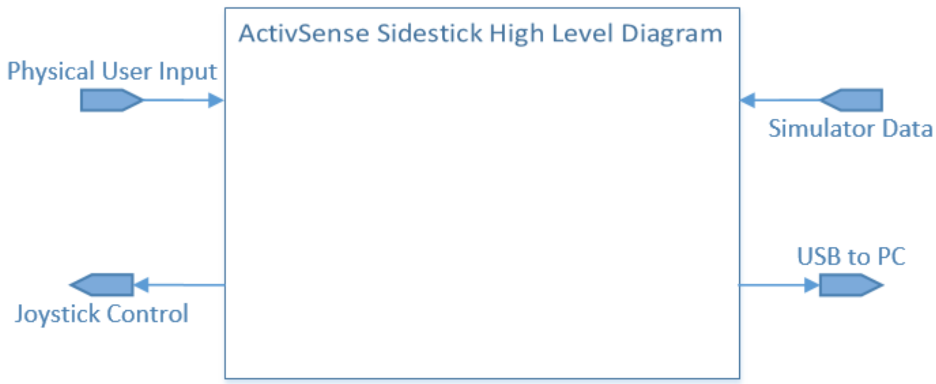


Figure 7- Level 0 Black Box Diagram

Level 1 Diagram

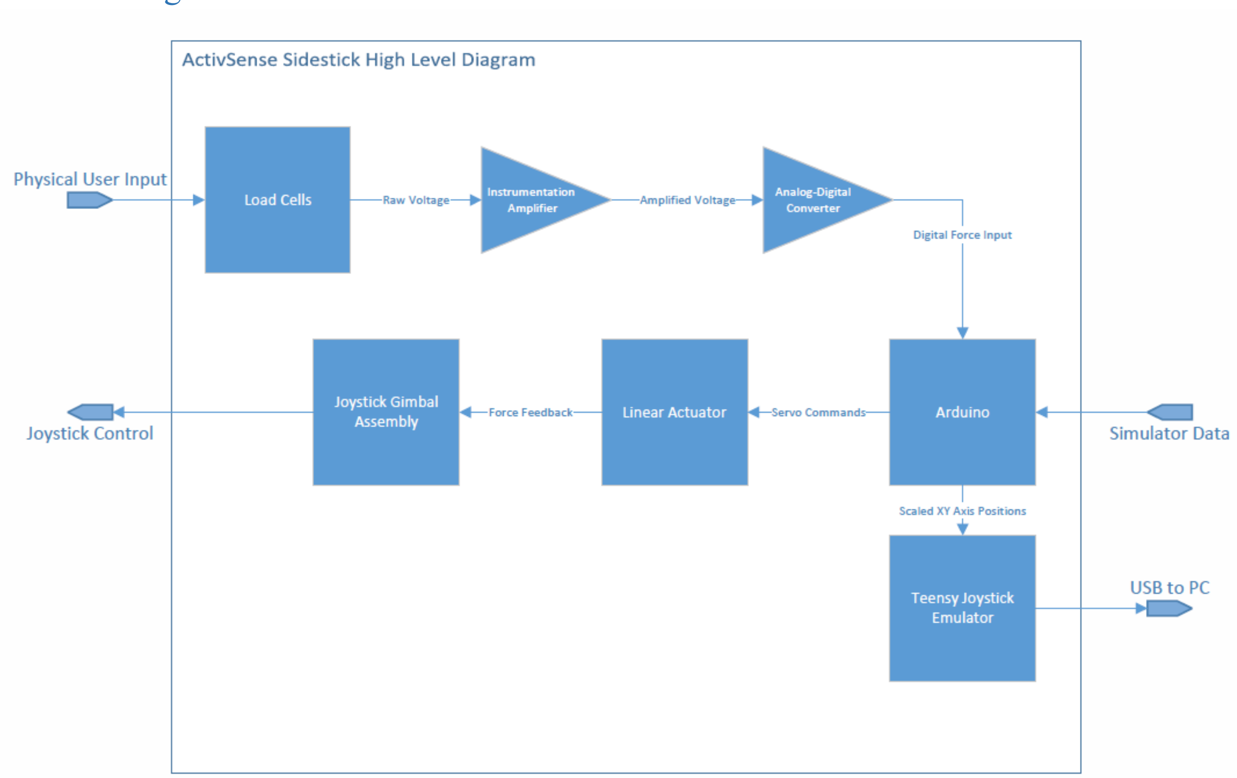


Figure 8 – Level 1 System Diagram

User Input

The system receives physical user input directly from the joystick mechanism. The user force is translated to an electrical signal through the use of 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

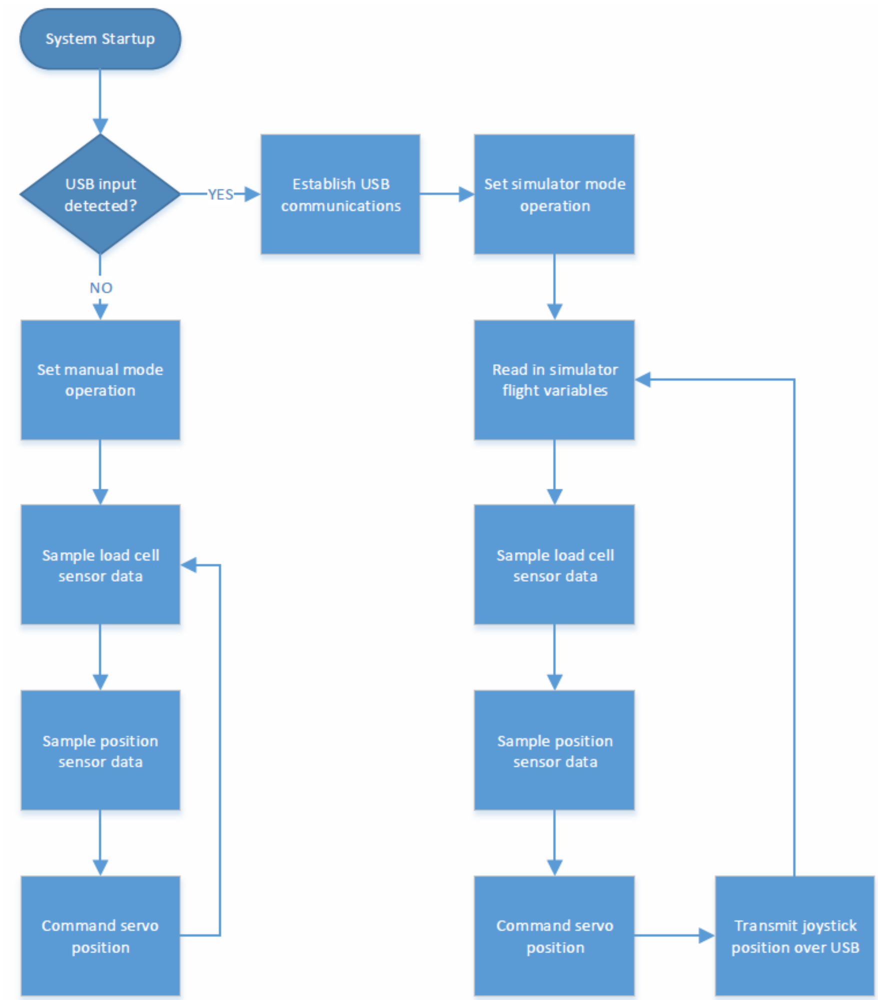


Figure 9 - Software Flow Diagram

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 Test and Verification

It is important that the requirements defined in the previous section are validated and verified throughout the design and build process. The following table links the requirements with a corresponding test in order to verify the requirement has been met. A requirements traceability matrix is provided to better visualize the hierarchy of tests and requirements.

System Test I.D.	Linked Requirement I.D.	Verified Requirement	Test Procedure
2.0.0	1.0.0	User programmable force gradients	Power up the sidestick system in normal operation. Run the associated software on a compatible PC and plug the sidestick USB cord into the PC. Program a minimum of three different force gradients and verify the sidestick responds correctly.
2.0.1	1.0.1	Simulator connectivity	Power up the sidestick system in simulator mode. Run the associated software and flight simulation program on a compatible PC and plug the sidestick USB cord into the PC. Begin flying the simulated aircraft and verify the sidestick responds appropriate to the simulator movements.
2.1.0	1.1.0	Avionics backward compatibility	Using an ARINC bus simulator, send standard ARINC data messages to the sidestick. Run the sidestick in debug mode to verify the sidestick receives and correctly decodes incoming ARINC messages.
2.2.0	1.2.0	Redundancy	Disconnect the power to the servos and jam the sidestick such that it cannot move. Verify the sidestick still produces correct flight control commands proportional to the applied force.
2.2.1	1.2.1	Redundancy	Disable one independent power supply that may be used by the servos or logic circuits. Verify the second power supply is sufficient to

			keep the sidestick operating normally.
2.3.0	1.3.0	Small form factor	Verify the final physical size of the sidestick does not exceed 24 x 24 x 24 inches using a measurement device.
2.3.1	1.3.1	Small form factor	Remove the existing grip on the sidestick and replace it with a different grip. Verify the replacement is easy to perform and does not cause inconsistencies in the force feedback.

Table 3 - System Test and Verification

	REQ ID	1.0.0	1.0.1	1.1.0	1.2.0	1.2.1	1.3.0	1.3.1
TEST ID	2.0.0	X						
	2.0.1		X					
	2.1.0			X				
	2.2.0				X			
	2.2.1					X		
	2.3.0						X	
	2.3.1							X

Table 4 -Requirements Traceability Matrix

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	May 29th, 2017
EE Senior Project Expo	Spring 2017	June 2nd, 2017

Table 5- 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 a number of 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.

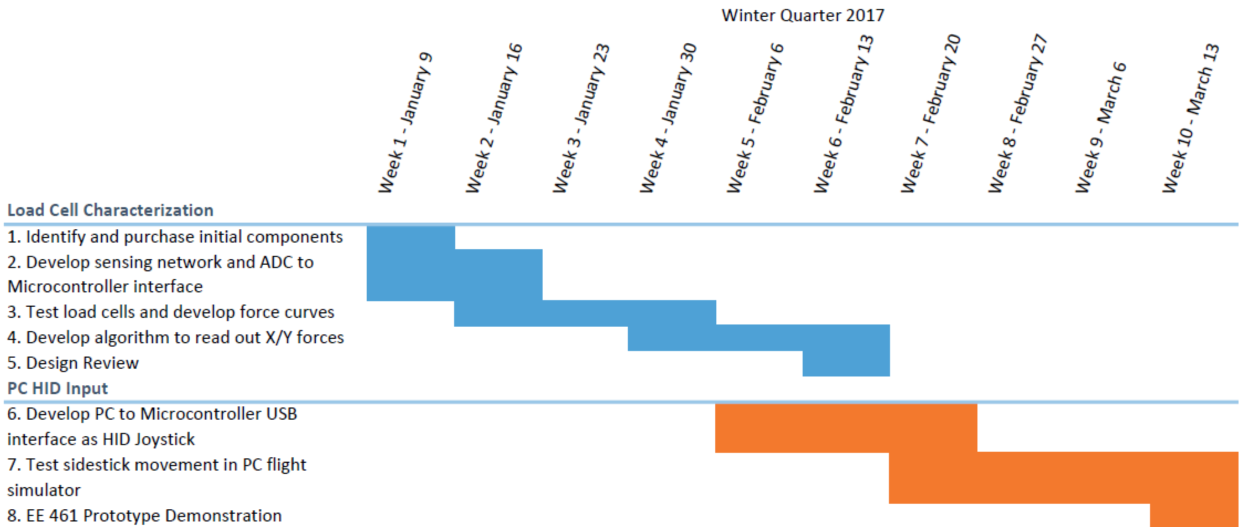


Figure 10 - Winter 2017 Schedule

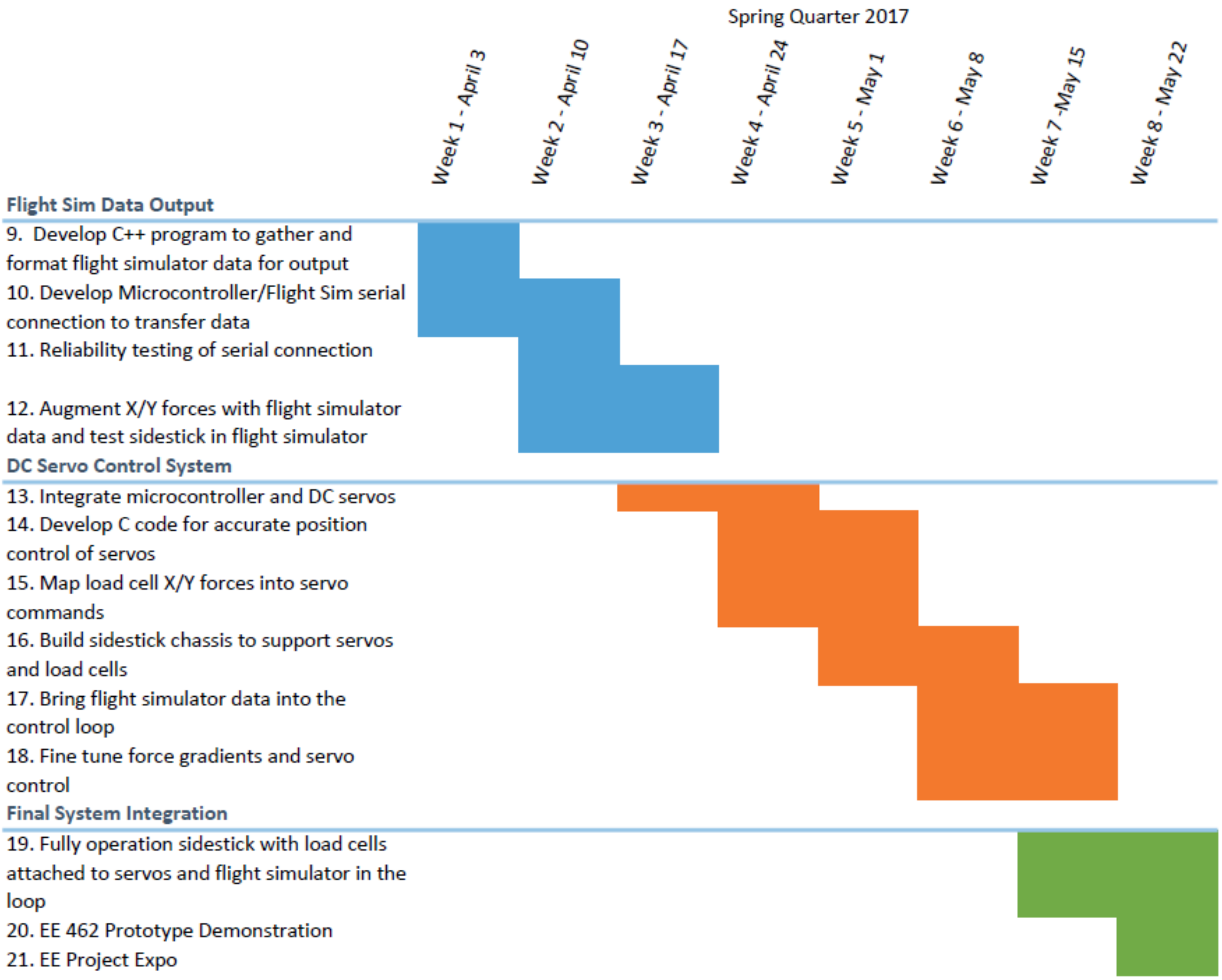


Figure 11 - Spring 2017 Schedule

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	April 17th

	○ Purchase and configure DC power supply for use with the servos	
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 Labs.

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 6 - 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.

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 a number of 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 of time. 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. With this in mind, 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 fairly 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 a number of 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.

Development

The design, production and testing of the sidestick required a number of technologies and electrical engineering theory. The servo motors will require control system theory and an understanding of pulse width modulation control. Sensing and analyzing strain gauge signals required analog electronics knowledge to convert small changes in resistance to a number that could span the entire range of a C *"int"* value. Development of the C and C++ code required extensive learning outside of the classroom.

Preliminary Design Analysis

Most of the design work will happen with the design of the sidestick chassis and gimbal mechanism. An initial design has been developed in a 3D modeling program as shown in the following figure.

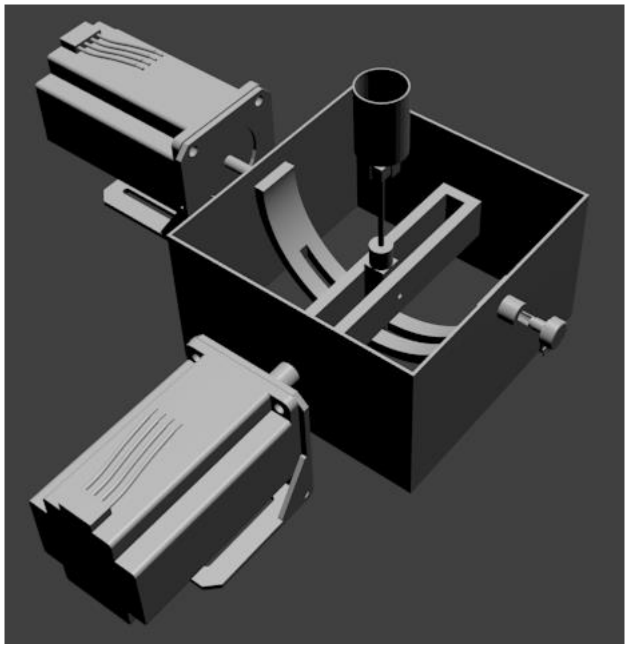


Figure 12- Complete System 3D Rendering

The challenge in the design of the sidestick grip is isolating both X and Y forces without hindering the movement of either axis. The initial design uses two load cells whose force sensing axes are perpendicular to each other, thus the X and Y forces should be able to measured independently.

Figure 13- Perpendicular Load Cell Configuration

This design will require the grip to have a larger diameter and has the possibility of being too large for a hand to comfortable grip over long periods of time. A separate design that accomplishes the goal of isolating the X and Y axes was developed as shown below. The two load cells are cut in half and attached to each other vertically. With force being applied directly to the top load cell it is likely the bottom load cell will experience the largest torque. Significant testing will be required to confirm this assumption and allow the forces to be normalized.

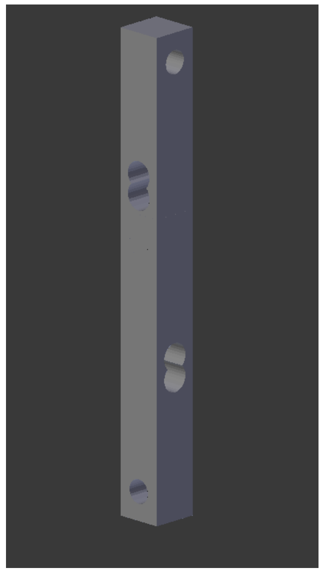


Figure 14- Vertical Load Cell Configuration

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