Electrical Engineering Department

California Polytechnic State University

Senior Project Report

Instrumented Control Column for Optionally Piloted Aircraft

June 12, 2023

Andrew Klein

Project Sponsor: Natilus

Advisor: Dr. Ben Hawkins

TABLE OF CONTENTS

1. Abstract 1
2. NEEDS – APPROACH – BENEFITS – COMPETITION (NABC) 2
2.1. Need 2
2.2. Approach 3
2.3. Benefits 3
2.4. Competition 4
3. Value Proposition Statement 5
4. General Introduction 6
5. Background 8
5.1. Controls 8
5.2. Sensor Solutions 8
5.3. Natilus Simulator 10
6. Marketing 11
6.1. Product Description 11
6.2. Technology and Market Research 11
6.3. Needs Hierarchy 12
6.4. Engineering Specifications 14
7. Block Diagrams 16
7.1. Partial Functional Decomposition 17
8. Software Overview 20
9. Risk Assessment 22
9.1. FMEA Discussion 22
10. Cost Estimation 22
10.1. Additional Resources 23
11. Project Schedule 24
11.1. Gant Chart Discussion 24
12. Project Plan 24
13. Impact Analysis 25
13.1. Ethics 25
14. Sensor Sourcing 27
15. Test Plan 27
15.1. Engineering Specification Verification 28
15.2. Component Testing 28

15.2.1. Load Cell Testing 29
15.2.2. String POT Testing 31
15.2.3. +/-5V To 0-5V Converter Testing 32
15.2.4. Development Board Testing 35
15.3. Integration Testing 36
15.3.1. Single Load Cell – Signal Conditioning – Dev Board 37
15.3.2. Dual Load Cells – Signal Conditioning – Dev Board (End-to-End) 39
15.3.3. All 4 String POTS - Dev Board 43
15.3.4. All 4 String POTS - Dev Board – MATLAB (End-to-End) 44
15.4. Discussion of Results 46
15.5. Future Improvements 47
15.6. Future Tests 48
16. Endnotes 49
17. References 49

FIGURES AND TABLES

Figure 1: N38T Artist Rendering 6
Figure 2: Generic Control Column CAD 7
Figure 3: String POT Example 8
Figure 4: Potentiometer Diagram 9
Figure 5: In-Line Load Cell Example 9
Figure 6: Natilus Simulator Screen During Setup 10
Figure 7: Natilus Simulator Screen and Cargo Hold Mockup 10
Figure 8: Weightings and Customer Requirement Breakdown 13
TABLE 1: Pairwise Comparison to Determine Rankings 13
TABLE 2: Engineering Specifications and Justifications 15
Figure 9: LVL 0 Block Diagram 17
TABLE 3: LVL 0 Block Description 17
Figure 10: LVL 1 Block Diagram 18
TABLE 4: LVL 1 Block Descriptions 18
Figure 11: Arduino Serial Sending Flowchart 18
Figure 12: MATLAB Serial Receiving/Plotting Flowchart 18

TABLE 5: BOM AND COST ESTIMATES 23
TABLE 6: PROJECT STAKEHOLDERS.... 26
TABLE 7: LOAD CELL SOURCING.... 27
TABLE 8: STRING POTENTIOMETER SOURCING.... 27
TABLE 9: COMPONENT TESTING PLAN 29
Figure 13: Amplified Load Cell on Oscilloscope 30
Figure 14: Connection Diagram for Simple Load Cell Test.... 30
TABLE 10: String Pot Resistance Measurements.... 31
TABLE 11: String Pot Voltage Measurements 31
Figure 15: LTSpice Schematic of Converter Circuit 32
Figure 16: LTSpice Simulations of Converter Circuit.... 33
Figure 17: Converter Design Implementation 34
Figure 18: Converter Output Verification.... 34
Figure 19: ADC Readout in Arduino Serial Monitor.... 35
TABLE 12: Integration Testing Plan 36
Figure 20: Single Load Cell Test Diagram 37
Figure 21: Known Load Test 37
Figure 22: Single Load Cell Tension Test 38
Figure 23: Single Load Cell Compression Test.... 38
Figure 24: Dual Load Cell Test Diagram 39
Figure 25: Dual Load Cell Test.... 40
Figure 26: Dual Load Cell Multimeter Result.... 40
Figure 27: Dual Load Cell Noise Scope Capture.... 41
Figure 28: Load Cell Amplifier Power 42
Figure 29: String POT Dev Board Tested 43
Figure 30: String POT Serial Plotter.... 43
TABLE 13: String Potentiometer Maximum Expected Travel 44
Figure 31: Single POT Simulink Scope.... 45
Figure 32: Quad POT Simulink Scope 45
Figure 33: Quad POT MATLAB Simultaneous Travel.... 45

APPENDICES

Appendix A: “FMEA: POTENTIAL FAILURE MODE AND EFFECTS ANALYSIS” **52**

Appendix B: “GANT CHART AND SCHEDULE COMPLETION BREAKDOWN” **54**

Appendix C: “SERIAL COMMUNICATION CODE/SCRIPTS” **56**

Appendix D: “NOTE ON NATILUS PROPRIETARY SIMULATOR” **60**

Appendix E: “FUTEK LOAD CELL AMPLIFIER INFORMATION” **61**

Appendix F: “FUTEK LOAD CELL CALIBRATION DATA” **63**

Appendix G: “LM13700 DUAL OPERATIONAL TRANSCONDUCTANCE AMPLIFIER INFORMATION” **65**

Appendix H: “LCM325 LOAD CELL INFORMATION” **67**

Appendix I: “SPI 12-3 STRING POTENTIOMETER INFORMATION” **69**

Appendix J: “ANALYSIS OF SENIOR PROJECT DESIGN” **71**

1. ABSTRACT:

Natilus, an aerospace company that is rapid-prototyping optionally piloted aircraft (OPA) for the shipping industry, needs a system that retrieves control column position data in order to manipulate flight simulator parameters in software. At present, a universally compatible system for all aircraft does not exist. Typically, established aerospace companies will sink significant time and money into developing proprietary systems for control column data retrieval as every aircraft is unique in its layout and linkage design. However, as a startup developing their first aircraft, Natilus does not have the privilege of modifying an existing sensor system to work with their HIL Iron Bird in the simulator. To successfully simulate flight controls in the Iron Bird, position data must be captured for the parameters pitch, roll, yaw, and throttle. Additionally, Natilus requires pilot input force data for pitch, roll, and yaw to verify human factors while "Hardware-in-the-Loop" testing with the Iron Bird control column.

This proposed electrical system shall mechanically integrate with the control column (and its peripherals) and digitally integrate with MATLAB and X-Plane simulators. It shall reduce the time and development costs for the first flight plane by providing only the necessary parameters for the simulation of the control surface responses to control column inputs while remaining easy to install, modify, and test. Additionally, this test system will become the foundation for the sensor system in the eventual production-scale aircraft. By utilizing a system that is perfectly compatible with the Natilus aircraft now — as it is being designed — the probability of issues arising with precision or integration bugs as the vehicle moves into production is reduced. Eliminating such threats to schedule at the prototyping stage will protect the product delivery date that Natilus has set for themselves and the other stakeholders.

2. NEEDS-APPROACH-BENEFITS-COMPETITION (NABC):

2.1. NEED

Natilus, an aerospace company that is rapid-prototyping optionally piloted aircraft (OPA) for the shipping industry, needs a system that retrieves control column position data in order to manipulate flight simulator software. At present, a universally compatible system for all aircraft does not exist. Typically, established aerospace companies will sink significant time and money into developing proprietary systems for control column data retrieval as every aircraft is unique in its layout and linkage design. However, as a startup developing their first aircraft, Natilus does not have the privilege of modifying an existing sensor system to work with their HIL Iron Bird in the simulator. They need a low-cost and quick way to achieve these results. To get the Natilus aircraft to the product delivery stage faster and cheaper than large competitors like Boeing and Airbus, a system of sensors that minimizes time for integration and data retrieval during testing is necessary.

Natilus operators will need to use this system to observe the aircraft in simulated flight. To successfully simulate flight controls in the Iron Bird, position data must be captured for the parameters pitch, roll, yaw, and throttle. Additionally, Natilus technicians will eventually require pilot input force data for pitch, roll, and yaw to verify human factors while HIL testing with the Iron Bird control column. As Natilus is expected to benefit financially from using a functioning simulator to garner attention from investors, the position sensing system is of higher priority. This proposed electrical system must mechanically integrate with the control column (and its peripherals) and digitally integrate with MATLAB and X-Plane simulators.

2.2. APPROACH

The Iron Bird control column will be linked to the vehicle's control surfaces via a network of pulleys, cables, pushrods, and control horns. This will provide the mounting/routing locations for the sensors. To successfully simulate flight controls in the Iron Bird, position data shall be captured for the parameters pitch, roll, yaw, and throttle. Additionally, pilot input force data for pitch, roll, and yaw shall be captured. Force sensing will be implemented with load cells in-line with pushrods and cables below the cockpit floor. By using load cells that measure both tension and compression, it is possible to use only one load cell per desired parameter. The input force from the pilot can be back-calculated from the location of force measurement in the system as it will be torqued. To read this data accurately, the load cell outputs will require signal amplification and conditioning (voltage level shifting, filtering). The position sensing will be implemented with linear string potentiometers in voltage divider configuration that can attach to the mechanical linkage and track the movement of pushrods and cables. A development board will serve as the effective "FCC" and will capture the analog sensor data through an ADC. This data will then be processed and sent to MATLAB and X-Plane simulation software. This system will be built in modules (Signal Conditioning, amplifiers, etc.), as that will simplify the testing done by Natilus technicians at specific circuit nodes later.

2.3. BENEFITS

The benefits of this approach are that the type of sensors used are extremely precise at a relatively low price. These in-line sensors measure both tension and compression, eliminating the need for expensive and large axial load cells. The cost reduction for Natilus will be significant, especially since the same sensors can be recalibrated and reused in the first flight aircraft after Iron Bird testing. Precision load cells and their calibration hardware can cost thousands of dollars. The proposed system will handle the conversion of the analog load cell values to digital values at a fraction of the cost. The data retrieval process will also be efficient in that using 1 sensor per desired datum will require less time to be allocated to maintenance and software tweaking. For Natilus autopilot and software technicians, this frees them up for other critical tasks that will push the Natilus aircraft delivery date forward. This approach achieves the appropriate precision through a 12-bit ADC, faster clock speeds on the development board, and updated sensor models that calibrate easily. This proposed system can easily grow with the Natilus iron bird project and will benefit from remaining modular. For example, if greater load cell precision becomes a priority later, Natilus can add a higher spec ADC (14-bit, 16-bit, etc.) without disassembling the whole thing. Ultimately, due to the rapid prototyping environment at Natilus, a system that is customizable to this extent is necessary to stay on schedule for first flight and product delivery.

2.4. COMPETITION

Different sensing options are often explored by other aerospace companies such as Boeing and Airbus. Torsional/Axial load cells are sometimes used, but these tend to be heavier, larger, and more costly. In an ideal workflow, the sensors will be designed around the control linkages and not the other way around. Since the current design uses pushrods, this will differentiate Natilus from its competition. Simplifying the methods to obtain force feedback by using robust tension + compression load cells will reduce weight, space usage, cost, and the number of analog inputs to the development board. The uniqueness of this approach is demonstrated across several factors but is largely driven by the fact that each new aircraft developed requires customization of its flight control systems to maximize precision and safety, as well as pass experimental aircraft regulatory guidelines. Natilus will stand out for having cleared this hurdle and doing so with only in-line sensors. The number of sensors in this approach is minimized at 1 sensor per desired datum. The proposed system can be operated by a single person and emphasizes ease-of-use by remaining modular. This approach also isolates the sensor locations to the space beneath the pilot's feet. This will simplify maintenance practices for Natilus technicians down the line as the final flight control systems from the Iron Bird testing will also be implemented into the "first flight" test plane. Maintenance simplicity is another beneficial factor that will make Natilus a formidable competitor in the industry.

3. VALUE PROPOSITION STATEMENT:

This project will deliver the first iteration of sensor systems that utilize control column position and pilot input force feedback data to interface with a flight simulator and verify human conditions inside the cockpit respectively. This shall be done at a low entry cost and on a fast timetable. The proposed systems shall be customized to work for Natilus's unique, experimental aircraft, and prioritize ease-of-use for Natilus technicians to operate and test with. By remaining modular and reducing the number of components used in competitor systems, this system shall be simple for Natilus to adapt as the aircraft matures. Additionally, this project shall prioritize the position sensing system as that has the most potential to bring in money for Natilus. However, a first attempt at the design of both sensor systems will be necessary to allow for the collection of valuable data. This data will contribute to the success of future iterations of this project that will see future versions of these systems implemented.

4. GENERAL INTRODUCTION:

The current, international shipping industry is split into air, sea, and land freight options. Shipping by air is fast and costly, while shipping via ocean freight is slow and cheaper. Shipping by land is similarly cheap and slow but is not applicable for US, trans-pacific freight endeavors. All current options produce significant carbon emissions. Natilus aims to revolutionize the shipping industry by matching the speed of current air freight endeavors while reducing operational costs by 60% and cutting carbon emissions by 50%. As an aerospace startup, Natilus is heavily dependent on investor financing. According to CEO Aleksey Matyushev, they are rapid-prototyping their smallest aircraft model with the hopes of garnering more industry attention.

The Natilus N38T is an optionally piloted aircraft currently in the prototyping phase. It is reported[1] to have a payload of 4.3 metric tons, a range of 900 nautical miles, and a cruising speed of 220 KTAS. This aircraft is classified as a 3.8-ton domestic flyer. Natilus GNC Engineer Kyle Sheehy stated in July of 2022 that this aircraft is currently moving out of SIL testing and into HIL testing with an Iron Bird [4].

Figure 1. N38T Artist Rendering

The Iron Bird is a full mockup of the aircraft's control surfaces and cockpit. The goals of this include seeing the control surfaces actuate with pilot input at the control column, verifying human conditions inside the cockpit, and using a physical control column to fly the simulator. To achieve this, a unique sensing solution is necessary. Established aerospace companies such as Boeing and Airbus, the current leaders in global air freight, have their own proprietary sensing systems that retrieve control column data and are compatible with their specific aircraft linkages. As each aircraft is unique in its dimensions and linkage routing, these sensing solutions must be modified and customized to fit the specific model.

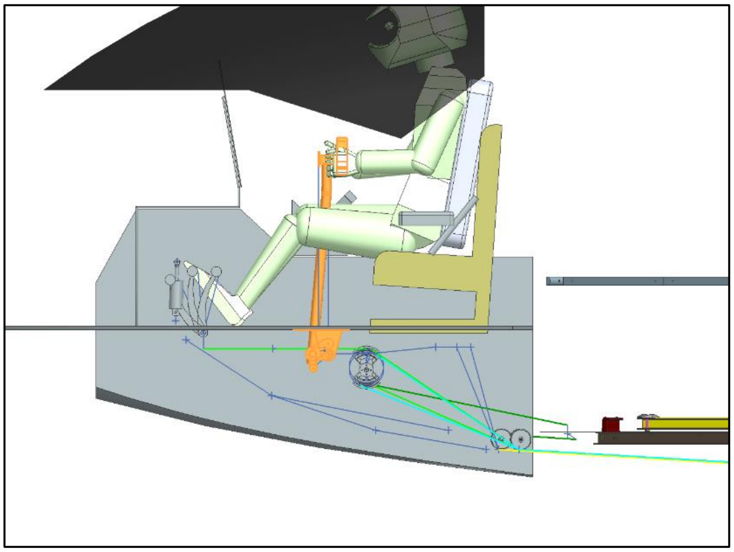


Figure 2. Generic Control Column CAD

This project aims to equip Natilus with a modular sensor system that is specifically compatible with their prototype aircraft. This system will provide the foundation of the N38T's flight controls as well as allow direct control of the simulator while installed in the Iron Bird. As an emerging competitor to Boeing and Airbus, Natilus hopes to achieve results over these industry giants by getting to the production phase at a quicker speed and for less money than they do. An instrumented control column sensor system that is easy for technicians to use and retrieve data from will be a crucial step towards attaining this goal.

5. BACKGROUND:

5.1. CONTROLS

For a pilot, the four essential controls are pitch, roll, yaw, and throttle. Pitch correlates to the angle of elevation and is controlled by pulling or pushing on the central pitch stick. The current Natilus prototype control column design[2] has this pitch stick running through the floor between the pilot's legs. This provides an excellent location for sensors as a linear pushrod off the base of this stick is easily accessible through the floor panel. The corresponding control surfaces are the Elevons. Roll is controlled by turning the yoke clockwise or counterclockwise. This yoke is attached to the top of the pitch stick and through gear, chain, and cable linkages, is routed below the floor also. Its corresponding control surfaces are the Ailerons. Yaw is controlled through the rudder pedals. There are two; one for each foot. Pushing on one rudder pedal pulls the other one back and vice versa. The rudder pedals are linked to the rudder through pushrods and cables. Lastly, throttle is a control for the engine output. The pilot adjusts throttle by adjusting a lever across an angle of around 0-90°. A throttle control is typically electronically linked to the control computer.

5.2. SENSOR SOLUTIONS

When position sensing, the traditional approach is to use potentiometers in voltage divider configuration and convert that analog data to a digital value with an ADC. This value can then be used to calculate distance or angle based on a calibration curve. Rotary POTs are the standard option for angular measurements and linear string or slide POTs are the typical first choices for linear position measurements.

Figure 3. String POT Example

String POTs are made by spring-loading a string that is connected to a rotary POT (blue component in Figure 3). As the string is pulled a linear distance away from the starting point, the rotary POT's wiper moves and the resistance of the device changes as the electrical path through a resistive strip lengthens (see Figure 4). When the tension on the string relaxes, the spring will cause it to retract, returning the POT wiper to its initial position.

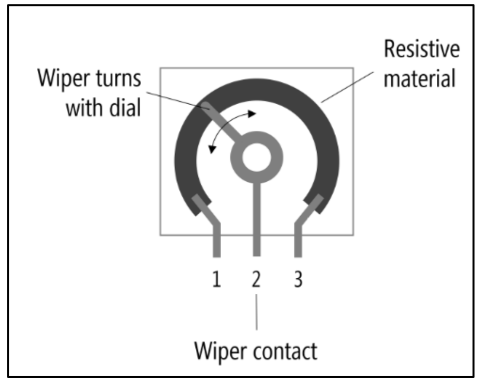


Figure 4. Potentiometer Diagram

According to Kyle Sheehy and Flight Controls Engineer Adrian Chabursky, precision string potentiometers are the most convenient way to receive linear position data since they can attach almost anywhere beneath the cockpit floor [4]. Additionally, any non-linearity in the linkage travel is tolerated mechanically and can be compensated for with a look-up-table in the development board software calculations.

Force Sensing is a bit more complicated, as the sensors themselves must both measure and withstand the full forces of the system. According to Chabursky, In-line solutions are ideal as they take up less space and allow for the direct transfer of force [4]. Pushrods off the pitch and yaw control make this implementation straightforward, as hardware already exists to add threaded ends and rod ends to load cells.

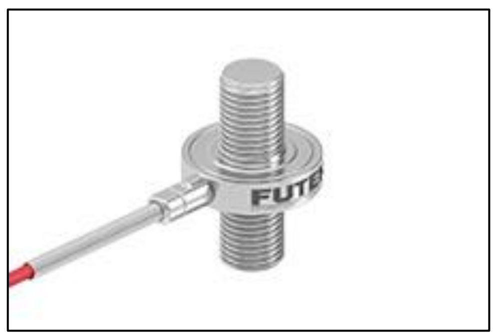


Figure 5. In-Line Load Cell Example

Load cells work by translating mechanical force into an analog voltage. Strain-gauge load cells are the most applicable to this project. This type of force sensor utilizes the effect of piezoresistivity to generate voltages. In metals and semiconductors, changes to the geometry of the material due to mechanical strain alter their electrical properties, most relevantly the electrical resistivity. These devices are often expensive and require a great degree of precision and process control during manufacturing to make the relationship between change in force and change in output voltage as linear as possible. Once reliable force sensors are implemented, additional hardware is required to condition the data signal and convert it to a digital value through an ADC.

A standard design practice is to not build the control system around the sensors, but to fit the sensors to the constraints of the control system. The roll force sensor will be the most difficult to implement, as the design of its linkages is still being completed and it is unsure whether it will have a pushrod or not. Alternative solutions that have been used by competitors would be to use sensors in-line with the cables themselves. Should the need arise, this mounting option may become viable in the future.

5.3. NAUTILUS SIMULATOR

The Natilus Simulator was created in MATLAB and Simulink R2021b by Kyle Sheehy[3] [4]. One major goal of this project is to feed control column data into this simulator to allow operators direct control of simulated aircraft flight with the N38T's control column in the Iron Bird. This simulation tool is proprietary to Natilus and is fully unique as it represents their aircraft needs, environmental conditions, control surfaces, navigation systems, etc. The Sim then sends data to X-Plane software to generate the display.

Figure 6. Natilus Simulator Screen During Setup

Figure 7. Natilus Simulator Screen and Cargo Hold Mockup

6. MARKETING:

6.1. PRODUCT DESCRIPTION

The Instrumented Control Column for an Optionally Piloted Aircraft project shall provide Natilus with a solution to their need for a reliable control column data collection system and methodology. The proposed system shall aid the Natilus team in meeting their ambitious product delivery schedule by taking a unique, modular approach to sensor system topology and requiring only one technician to operate it. Both pilot input force and control column parameters shall be capturable by the system, allowing a pilot to fly the simulator from the N38T Iron Bird cockpit. Because the N38T is being designed from the ground up as a prototype, the control column will not be compatible with the solutions used in other competitor aircraft. This proposed system boasts the critical benefit of being built specifically for the Natilus vehicle. By fitting, sizing, and calibrating this system to the N38T specs, dimensions, forces, and throws, a truly novel and cost-effective solution can be implemented in a timely manner. As a result, Natilus can confidently advance their project through the HIL testing phase and remain on schedule.

6.2. TECHNOLOGY AND MARKET RESEARCH

The technology used to implement this system is not revolutionary. The design process and the result itself are the unique elements that are marketable. Since every aircraft undergoes unique control column design in its early stages, the compatibility of the control column sensor system can become a progress-halting problem very early on in the aircraft's product lifespan. Adrian Chabursky, a Natilus flight controls engineer used to work on a project[4] for Northrup Grumman in which a similar method utilizing string potentiometers was employed for position sensing [4]. In addition to the overall vehicular dissimilarities, one major difference in the Natilus system is that the pilot input force will also be captured to verify human conditions inside the Iron Bird cockpit.

The implementation of these two data retrieval processes in a modular form allows Natilus to have a system that grows and evolves along with the aircraft through its prototyping phase. It is important to note that most sensor systems developed for this purpose by competitors are either modifications of similar models by the same company or are built from the ground up for production models. Because of the unique phase of testing and marketing that Natilus is experiencing as a startup, the custom approach is essential as it allows them to build the foundation of their own flight control column testing procedures. Investors will sit down in the Iron Bird cockpit and move the controls while seeing a simulator react to their inputs. This will allow Natilus to start bringing in more money and garnering more industry attention by contributing to a high-quality HITL design. This phase of prototyping will be critical to Natilus and their future as a startup. Similarly, this will aid in establishing precedents which expedite the future progress of the N38T and their larger aircraft models through the prototyping and verification phases as the Natilus technicians shall also have past work to reference and modify.

6.3. NEEDS HIERARCHY

It is with this market knowledge and these customers in mind that specific needs were weighed against each other. This allowed for a priority of needs to be established and for quantifiable requirements to be generated from qualitative requirements. These priorities were also affected by direct input from Natilus Engineers; Kyle Sheehy, Adrian Chabursky, and Yohannes Araya, and CEO Aleksey Matyushev [4]. The primary driving factor in deriving the weightings was the customer's expected experience with the system and determining which elements will contribute most towards Natilus's satisfaction with the product. As the project progresses, there is always a possibility that these weightings will be further affected by changes made to the control column and its linkage as it is being designed in parallel to this system.

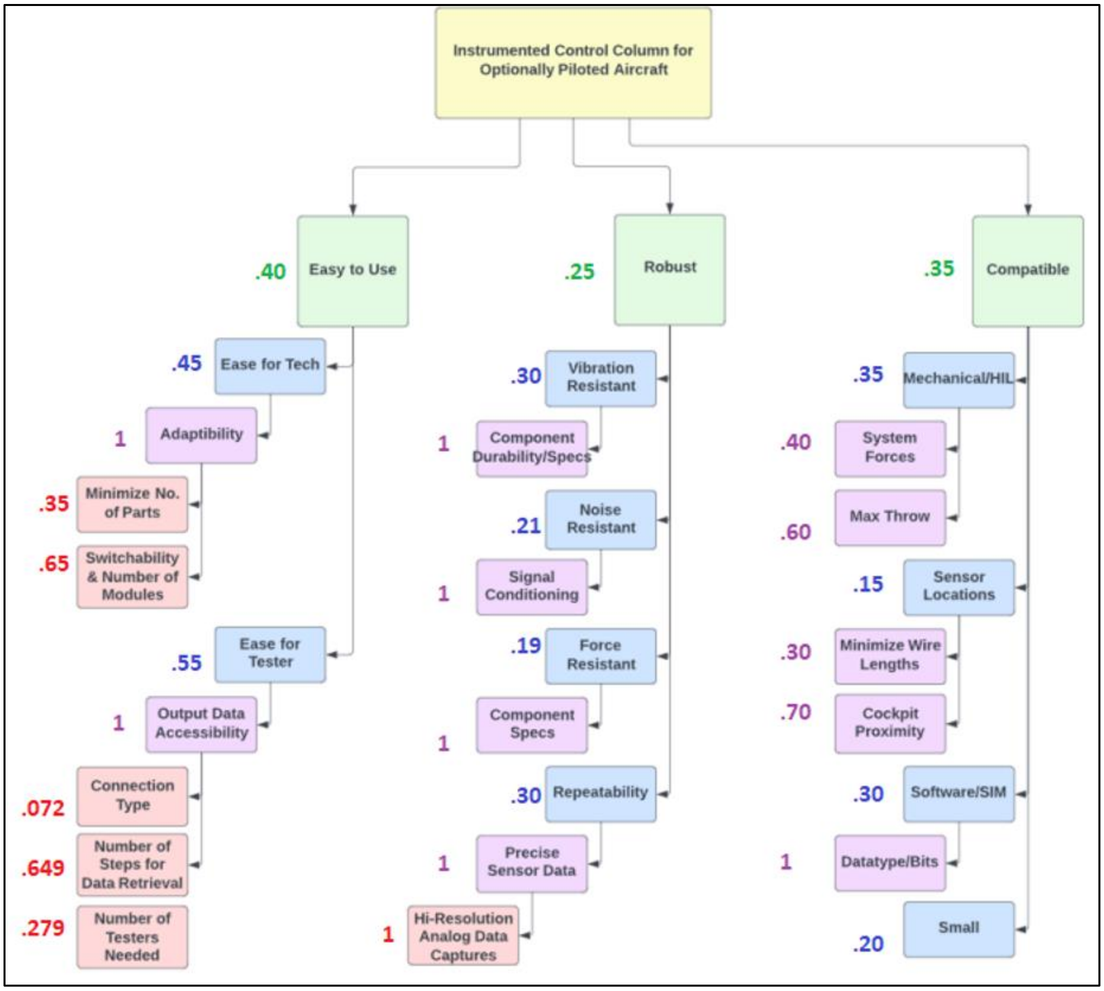


Figure 8. Weightings and Customer Requirement Breakdown

TABLE 1

PAIRWISE COMPARISON TO DETERMINE WEIGHTINGS

Pairwise Comparison to Determine Rankings

OUTPUT DATA ACCESSABILITY:

	Connection Type	Number of Steps for Data Retrieval	Number of Testers Needed	Geometric Mean	Weights
Connection Type	1	0.14286	0.2	0.305712747	0.071927942
Number of Steps for Data Retrieval	7	1	3	2.758924176	0.649118297
Number of Testers Needed	5	0.33333	1	1.185627149	0.278953761

6.4. ENGINEERING SPECIFICATIONS

Final quantitative requirements with target values or ranges were established based on the weightings in the Needs Hierarchy above. These engineering requirements are the constraints that helped inform the design decisions and priorities. Some of these values came directly from Adrian Chabursky, such as max system loads and travels [4]. Others were derived directly from the Needs Hierarchy in combination with system functionality knowledge and expectations. Most are perfectly quantitative and have units that are bound and realistic. However, there are several specifications that are more select, such as "Data output from the development board should be accessible by MATLAB through a USB Connection.". Despite this being more of a checklist item, it relates to the precision of the system and the number of digital values available per millivolt in an ADC conversion. In a similar fashion, all the other checklist specifications are verifiable, traceable and. The following engineering specifications were all translated to be unambiguous such that they would be directly verifiable through testing and backwards traceable to customer requirements.

TABLE 2

ENGINEERING SPECIFICATIONS AND JUSTIFICATIONS

Marketing Requirements	Engineering Specifications	Justification
2a, 3a	Pitch load cell should withstand & measure up to 1500 lbs.	Max system force at this point is calculated at 1416 lbs.
2a, 3a	Yaw load cell should withstand & measure up to 1000 lbs.	Max system force at this point is calculated at 944 lbs.
2a, 3a	Roll load cell should withstand & measure up to 1500 lbs.	The force at this point of the system is unknown, however, it is not going to exceed that of the pitch load cell.
3b	Pitch string POT should measure 4.75 inches.	The max total travel for pitch will not exceed 4.50 inches.
3b	Yaw string POT should measure 4.75 inches.	The max total travel for pitch will not exceed 1.75 inches.
3b	Roll string POT should measure 4.75 inches.	The max total travel for pitch will not exceed 4.50 inches.
1c, 2d, 3e	Load cell data precision should be at least .5 lbf.	This will allow for greater precision and signal integrity.
1c, 2a	System should be built with connectors and minimized soldering.	Solder will become brittle and degrade faster under aircraft vibrational forces.
1e	The system should require only one operator or technician at any given time.	Man-hours are a precious resource in a rapid-prototyping environment.
1	Data output from the development board should be accessible by MATLAB through a USB Connection.	This will allow technicians and operators to run the simulator with a reliable data connection.
2c, 3d	In-line load cell sensors should have thread type ends.	These will likely go in-line with pushrods and require a simple & reliable method to transfer force.
3f	In-line load cells should have an outer diameter less than 2”.	The space beneath the floor is limited and sensor size should be minimized as much as reasonably possible without compromising performance.
3f	String POTs should be smaller than 3” in diameter.	The space beneath the floor is limited and sensor size should be minimized as much as reasonably possible without compromising performance.
1a, 1b, 1d	Data retrieval steps should take less than 2 minutes from power up to simulator function.	This system can’t add unnecessary complexity or require constant troubleshooting. Time and efficiency are Natilus’s priorities.

MARKETING REQUIREMENT LIST	1a. Minimize No. of Parts 1b. “Switchability” & Number of Modules 1c. Connection Type 1d. Number of Steps for Data Retrieval 1e. Number of Testers Needed 2a. Component Durability Specs 2b. Signal Conditioning 2c. Component Specs 2d. Hi-Resolution Analog Data Captures 3a. System Forces 3b. Max Throw 3c. Minimize Wire Lengths 3d. Cockpit Proximity 3e. Datatype/Bits 3f. Small

7. BLOCK DIAGRAMS:

To arrive at a detailed and realistic top-level design for this sensor system, partial functional decomposition was employed. This allowed the expansion of the design from the already defined inputs and outputs of the system. If a pilot inputs force and positional change, they expect to see the changes logged and acted upon in the SIM software. There is also an expected input for power to excite the sensors and provide energy to the active components and microprocessor. This is specific enough for the LVL 0 decomposition. To elaborate on the top-level design further, a LVL 1 decomposition was also utilized. This level identified a bus to route the power as well as sensors to translate the pilot inputs. The pilot inputs are then processed as analog voltages and conditioned by an amplifier/level-shifter. These signal voltages are converted to digital values by the microprocessor on-board ADC and sent to the computer. The computer interfaces with MATLAB Simulink to run the Natilus SIM program.

7.1. PARTIAL FUNCTIONAL DECOMPOSITION

LVL 0:

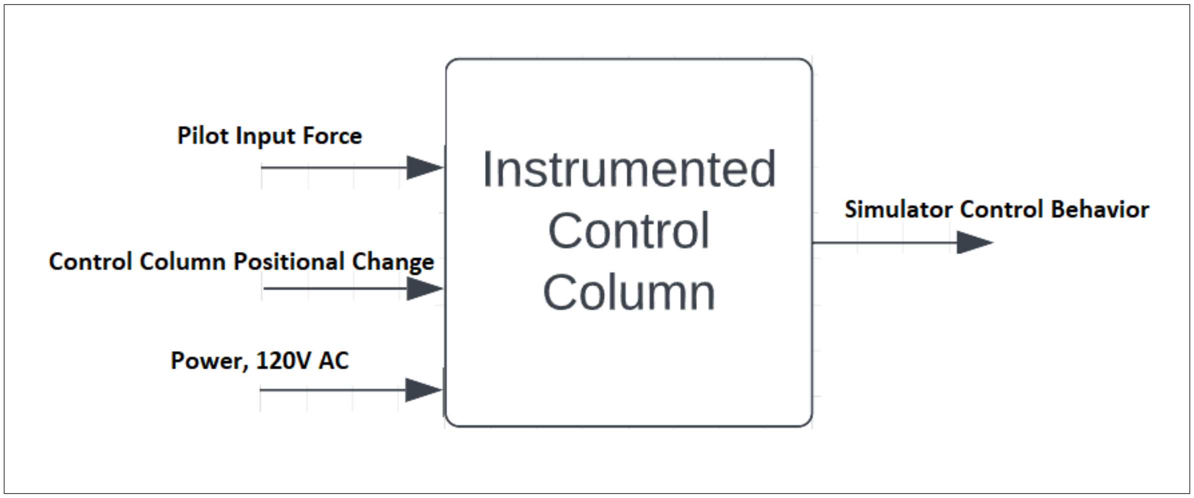


Figure 9. LVL 0 Block Diagram

TABLE 3

LVL 0 BLOCK DESCRIPTION

Module:	**Instrumented Control Column**
Inputs	Pilot Input Force: - Pitch, < 2000 lbf - Yaw , < 1000 lbf - Roll, < 2000 lbf Control Column Positional Change: - Throttle, < 4.75 inches - Pitch, < 4.75 inches - Yaw, < 1.75 inches - Roll, < 4.50 inches Power, 120V AC rms, 60Hz
Outputs	Simulator Control Behavior
Functionality	Allow a technician or operator to observe and monitor control column data in the Natilus MATLAB Simulation software.

LVL 1:

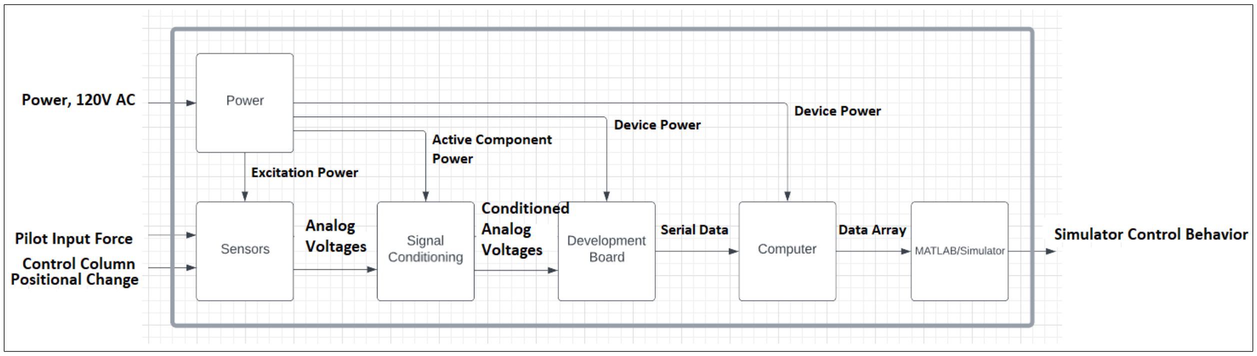


Figure 10. LVL 1 Block Diagram

TABLE 4

LVL 1 BLOCK DESCRIPTIONS

Module:	**Power**
Inputs	Power, 120V AC rms, 60Hz
Outputs	- Excitation Power, V DC, Value TBD during design/sourcing - Active Component Power, V DC, Value TBD during design/sourcing - Device Power (Dev. Board), V DC, Value TBD during design/sourcing* - Device Power (Computer), Value TBD during design/sourcing **Most Development boards run on either 3.3V or 5V DC*
Functionality	Provide power to circuit and system elements.
Module:	**Simulator**
Inputs	Data Array, integer, Scaling factor and output range TBD during design
Outputs	Simulator Control Behavior: - Data Storage in Variables - Plots - Simulated Flight Control
Functionality	Receives final flight control data and assigns it as inputs to the MATLAB simulator script and Simulink blocks to generate, analyze, and visualize simulated flight.
Module:	**Sensors**

Inputs	Pilot Input Force: - Pitch, < 2000 lbf - Yaw , < 1000 lbf - Roll, < 2000 lbf Control Column Positional Change: - Throttle, < 4.75 inches - Pitch, < 4.75 inches - Yaw, < 1.75 inches - Roll, < 4.50 inches Excitation Power, V DC, Value TBD during design/sourcing
Outputs	Analog voltages, Value TBD during design/sourcing
Functionality	Generate analog signals from the pilot inputs to force and positional change.
Module:	**Signal Conditioning**
Inputs	Analog voltages, 2-100mV range (Value TBD during final design/sourcing) Active Component Power, V DC, Value TBD during final design/sourcing
Outputs	Analog voltages, 0-5V DC, Amplification value TBD during design/sourcing
Functionality	Takes the unprocessed analog sensor data and scales it to the necessary
Module:	**Development Board**
Inputs	Analog voltages, 0-5V DC Device Power (Dev. Board), V DC, Value TBD during design/sourcing* **Most Development boards run on either 3.3V or 5V DC*
Outputs	Digital value, Scaling factor and output range TBD during design
Functionality	Captures the amplified sensor data and converts it into a digital value to send to the computer.

Module:	Computer
Inputs	Serial Data digital value, Scaling factor and output range TBD during design Device Power (Computer), Value TBD during design/sourcing
Outputs	Data Array, integer, Scaling factor and output range TBD during design
Functionality	Receives the digital data and packages it for MATLAB Simulation.

8. SOFTWARE OVERVIEW:

The essential element of this project that allowed for the interfacing of the development board with the MATLAB software was serial communication. For the exact code used to send data from the Arduino and an example MATLAB script used to receive data see Appendix C.

This Arduino code can also be used to capture load cell data. Instead of sending the data to the Serial Port, the digital values are plotted and scaled within the Arduino IDE.

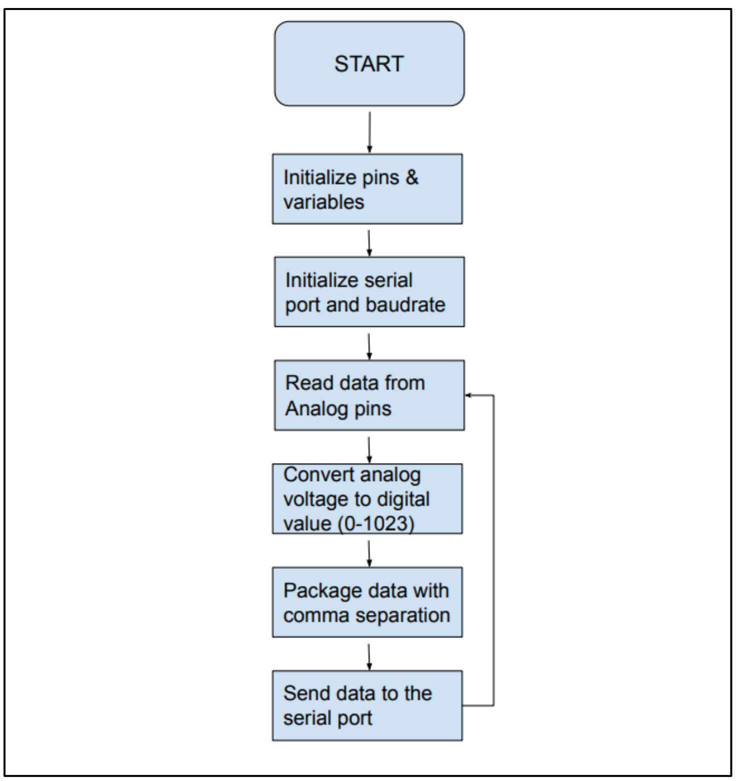


Figure 11. Arduino Serial Sending Flowchart

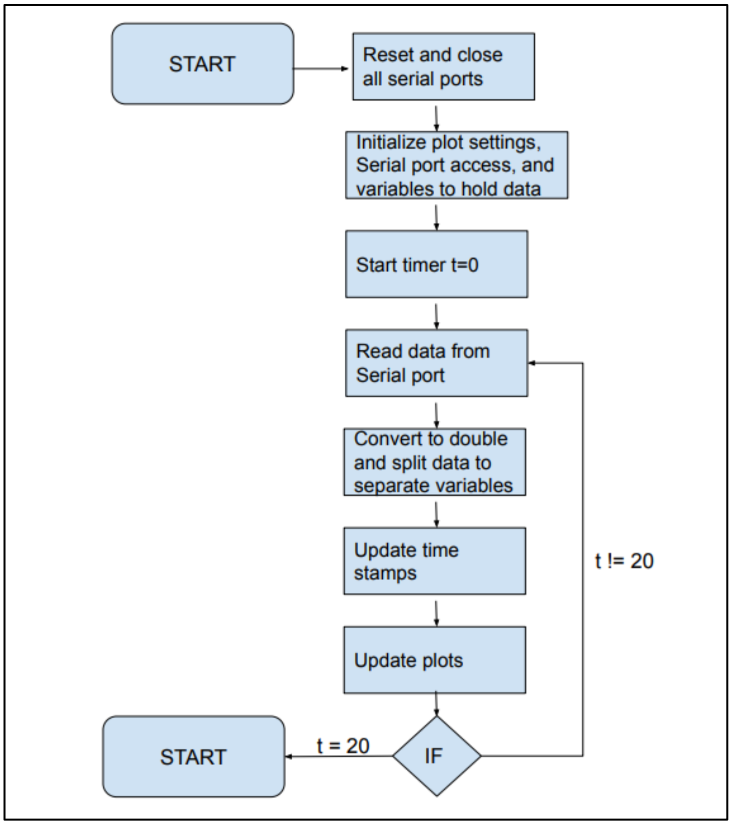


Figure 12. MATLAB Serial Receiving/Plotting Flowchart

For proprietary reasons details on the Natilus simulator will be excluded from this report see Appendix D. In its place is included a MATLAB script that will allow data to be read into MATLAB.

Both the sending and receiving programs are simple. Two things must be configured within the IDE for serial communication to take place properly. First the serial baudrate should match in both programs. In the included examples the default value 9600 was used. Without aligning this parameter, the transfer of data will not be synchronized properly and can cause MATLAB to return an error. The other critical parameter is the terminator. This gets sent at the end of each serial communication and tells the receiving program that Arduino has finished sending a package of information. If MATLAB expects the wrong one this can be configured by editing the serial object in MATLAB and selecting the desired terminator in the Arduino serial monitor window.

9. RISK ASSESSMENT:

9.1. FMEA DISCUSSION

Preliminary risk assessment was conducted via an FMEA (see Appendix A). The results showed that most potential failure mediums were expected to remain at a low probability of occurrence. This would imply that the current design controls are satisfactory for the system at this stage. Additionally, the RPN numbers listed indicated little necessary action for most items in the list. If a failure were to occur, there would be no risk of harm to the operator and little risk of damage to the equipment. Thus, most of these potential threats can be mitigated in the design phase by sourcing good sensors and components and including appropriate safety margins.

To ensure that the design is stable and little variation is introduced, the components will be assessed and tested to ensure that they are within spec. This could be done with a simple parametric test for smaller circuits and components and Monte Carlo analysis for larger circuits or subsystems. Another way to build in stability would be to add recalibration functionality to the sensor system. This shall minimize the variance between individual testing runs and provide assurance to any technician operating the system that the data captured is meaningful.

10. COST ESTIMATION:

A simple estimation of cost based on material sourcing and estimated hours worked is displayed in BOM format in Table 5. This outlines the necessary materials along with the initial approximation of the hours necessary to complete this project.

TABLE 5

BOM AND COST ESTIMATE

Sub	Sub	Sub	Sub	Description	Qty	P/N	Document	MFG	MFG P/N	LT - Weeks	1kpcs Price (USD)	Price*QTY
System Build - Natilus N38T Instrumented Control Column					1	2000		Custom		6		0
1	Final Assy - Sensor System				1	2001	Instr	Custom	---	1		0
	1				1	2002	Instr	Custom	---			0
		1	Voltage Converter + Level Shifter		1	2003	Custom	Custom	---	6		0
			1	Resistor, 100k 5%	20		Spec		---	2	0.01	0.2
			2	Resistor, 110k 5%	10		Spec		---	2	0.01	0.1
			3	Resistor, 40k 5%	10		Spec		---	2	0.01	0.1
			4	Resistor, 5.1k 5%	10		Spec		---	2	0.01	0.1
			5	Capacitor, 100pF Ceramic 50V	10		Spec		---	2	0.01	0.1
			6	Capacitor, 10pF Ceramic 50V	20		Spec		---	2	0.01	0.2
			7	Breadboard	6		Spec		---	2	2.00	12
			8	Power Supplies	3		Spec		---		5.99	17.97
			9	LM13700	8		Spec	TI	---		1.00	8
			10	20' wire	1		Spec		---		5.00	5
		2	Microprocessor		1		Spec		---	4	0.7280	0.728
			1	Arduino Uno	2		Spec	Arduino	---	1	10.00	20
			2	Micro USB	2		Spec	Arduino	---	1	4.00	8
		3	Sensors									0
			1	String POT	5		Spec			2	369.4900	1847.45
			2	Load Cell	3		Spec	Futek			825.0000	2475
			3	Load Cell Amplifier	3		Spec	Futek			575.0000	1725
		5	Labor, test, overhead, profit (all in) of Sub assembly		1			---		---		0
										Material Total		6119.948
							If made in USA		0.5hrs x $40/hr	Weekly Hours		
										Worked	3.00	
										Weeks	28	
									Salary Est.	$27/ hour		
										Total Labor Cost	2268.00	

10.1. ADDITIONAL RESOURCES

Other resources that were necessary for completion of this project include, but are not limited to, the Natilus Proprietary SIM that is built out in MATLAB’s Simulink, a Natilus work computer, Cal Poly and Natilus-owned benchtop test equipment, and a means of transportation between San Diego and San Luis Obispo (Car, Train, Airplane).

11. PROJECT SCHEDULE:

11.1. GANT CHART DISCUSSION

The project schedule was decided and organized using a Gant Chart (see Appendix B). This chart shows the Define phase lasting 99 days from 6/1/22 to 10/17/22, the Design phase lasting 31 days from 10/17/22 to 11/28/22, the Build phase lasting 27 days from 1/9/23 to 2/14/23, the Validation phase lasting 67 days from 2/15/23 to 5/18/23, and the project Release phase taking place over 17 days from 5/19/23 to 6/12/23. There are several key deadlines to note, which include the advisor design reviews on 11/25/22 and 2/14/23 , the final report submission on 6/9/23, and the senior project expo occurring during the weekend of 6/9/23 to 6/12/23.

12. PROJECT PLAN:

The project follows the schedule outlined in the Appendix B Gant Chart. Communication with project advisors and Natilus supervisors remains constant throughout the design phase and onward. Primary testing occurs at Cal Poly in San Luis Obispo, with a possible round of testing at the Natilus Hangar at Brown Field pending the completion of the mechanical linkages on the Iron Bird. However, this is not expected to be completed during the timeline of this project. The project will be considered a success if the engineering requirements are met, and the customer is satisfied. If data cannot be read accurately off the position sensors and passed into the MATLAB SIM program, then the project is incomplete as it is currently defined. Similarly, if no solution is proposed for force sensing and data retrieval, this project will be considered incomplete.

Some additional skills that may be necessary to develop further include, but are not limited to, analog circuit design, PCB design, basic aircraft controls, control systems, technical writing, critical thinking, and interfacing MATLAB with hardware.

13. IMPACT ANALYSIS:

13.1. ETHICS

By putting first, the health, safety, and welfare of the public, this project was designed carefully such that Natilus flight control systems will have a solid foundation. It remains crucial to report any gaps in technical competency moving forward, and to be realistic in the scope of this project and the extent to which it can be applied within the Natilus Iron Bird and prototype aircraft. Natilus, being on the cutting edge of the freight shipping industry, strives to mitigate the societal implications of its new drone technology by introducing it first as an optionally piloted aircraft (OPA) [4]. This will allow social and legal systems to catch up to the point that this tech can be regulated and implemented safely. Additionally, it is important to be aware of any conflicts of interest and choose honesty and integrity over personal interests. This will not only allow for greater success within this project but will also allow Natilus and Cal Poly to build a relationship of trust and respect with the public going forward.

By sourcing materials that were not overly detrimental to the environment (without significant detriment to society or cost) and selecting methods during the build phase of the project that did not pollute or waste, this project can claim to use sustainable manufacturing practices. Furthermore, Natilus has partnered with ZeroAvia to implement the ZA600 hydrogen-electric engines for zero emission propulsion into the final production aircraft. By helping Natilus become an industry competitor through success in the Iron Bird HIL testing phase this project will be contributing to the emergence of a revolutionary, sustainable shipping option.

TABLE 6

PROJECT STAKEHOLDERS

Stakeholder	Description
Natilus SIM Technicians	Includes: -Natilus Test Technicians -Flight Control Engineers -GNC Engineers -Autopilot Engineers Gather and analyze data, adapt and maintain system.
Natilus SIM Operators	Includes: -Natilus Employees -Investors Interact with control column as "pilot".
Natilus Engineering Team	Can make engineering decisions based on data.
Natilus Marketing Team	Can report Progress on Iron Bird HIL.
Natilus Shareholders	Company value rises as product gains attention.
Cal Poly Students	Gain technical experience and access to report documentation through the library.
Cal Poly EE Department	Gains new Senior Project Report, Expo attention, and Natilus connection.

Balancing the interests of all stakeholders and guiding the project along a sustainable and ethical route shall be critical to this project's success. There are many people who have a stake in this project, and even more who will be affected by the technology Natilus hopes to develop and release. This necessitates the practice of great care while treading these ethical lines, as decisions made now in this project have the potential to affect the future of the whole company.

14. SENSOR SOURCING:

TABLE 7

LOAD CELL SOURCING

Component	Cost	Link	Status -- Date
Pitch Load Cell	$825.00	Miniature Threaded In Line Load Cell LCM325 : FSH04009 (futek.com)	Arrived
Yaw Load Cell	$825.00	Miniature Threaded In Line Load Cell LCM325 : FSH04009 (futek.com)	Arrived
Roll Load Cell:	$825.00	Miniature Threaded In Line Load Cell LCM325 : FSH04009 (futek.com)	Unordered -- Budget Constraint 3/23/2023 PROJECT WILL USE OTHER LOAD CELLS TO DEMO. **NATILUS IS WAITING FOR FUNDING AND THE POSITION SENSING IS THE PRIORITY SYSTEM**

TABLE 8

STRING POTENTIOMETER SOURCING

Component	Cost	Link	Status
Pitch Potentiometer	$369.49	SP1-12-3 MeasurAppendix lement Specialties | Mouser	Arrived
Yaw Potentiometer	$369.49	SP1-12-3 Measurement Specialties | Mouser	Arrived
Roll Potentiometer	$369.49	SP1-12-3 Measurement Specialties | Mouser	Arrived
Throttle Potentiometer	$369.49	SP1-12-3 Measurement Specialties | Mouser	Arrived

15. TEST PLAN:

15.1. ENGINEERING SPECIFICATION VERIFICATION

There were several criteria for the sourced sensors that would verify crucial engineering specifications. First, the range of weight for which each load cell can measure was verified through the supplier's datasheet. The LCM325 load cell can withstand and measure up to 2000lbf. This is more than sufficient for the pitch and yaw applications within the Iron Bird. The roll load cell was not ordered due to current funding limitations at Natilus. However, the rest of the testing process would follow the same steps as the other two load cells. For the scope of this project, that degree of completion will suffice. These load cells have threaded ends and a diameter of .96in, further satisfying the requirements for these sensors outlined in the engineering specifications section.

The range of distances measurable by the string potentiometers can also be verified by the supplier datasheets. The SP1-12-3 can measure up to 12.5in. This is more than sufficient for pitch, roll, yaw, and throttle applications in the Iron Bird. The dimensions of the string potentiometers are 2in x 1.9in, which is within spec for the space requirement of approximately 3in diameter per sensor.

15.2. COMPONENT TESTING

Even though these sensors come from reputable sources, they were checked for any issues or defects along with other components in the system before moving on to system integration testing. This consisted mainly of basic electrical tests for the sensors and a data communication test for the microcontroller.

TABLE 9

COMPONENT TESTING PLAN

Component Tests	
Load Cell	Connect the load cell and amplifier as shown according to the datasheet diagram. Using an oscilloscope, confirm an analog output that changes within the range of 1mV up to 50mV as a small force is applied. For tension/compression load cells, check for both a positive and negative analog voltage output.
String POT	Connect the sensor in voltage divider configuration. Check that the max voltage at max throw is equal to the input voltage of the voltage divider. Confirm the linearity of the sensor over the distance range. Measure the resistance and full extension and resting position of each POT.
Load Cell Amplifier/Signal-Conditioning	Simulate the voltage converter circuit in LTSpice. Confirm the simulation readout, then build with real components. Give it an input of +/-5V and determine if the output behaves as expected (0-5V). Confirm the gain parameters scale the output to the range for the 12-bit ADC (+/-5V).
Development Board	Connect the Dev board to the computer and verify that it is discoverable as a device and that data transfer is possible through a USB cable. Confirm that power is delivered to the board and that the ADC can read a known analog voltage.

15.2.1. LOAD CELL TESTING

In Figure 13, the FUTEK LCM325 is shown being excited in both the positive and negative direction from ground. This scope capture demonstrates how the change in forces on the load cell results in a change in voltage at the output. (Compression for negative and tension for positive). These two load cells and their amplifiers (see Appendix E) are confirmed to be operational via this method. For the additional roll parameter load cell (see Table 7) that will be sourced by Natilus after this project, this same process can be repeated to verify that it is operational.

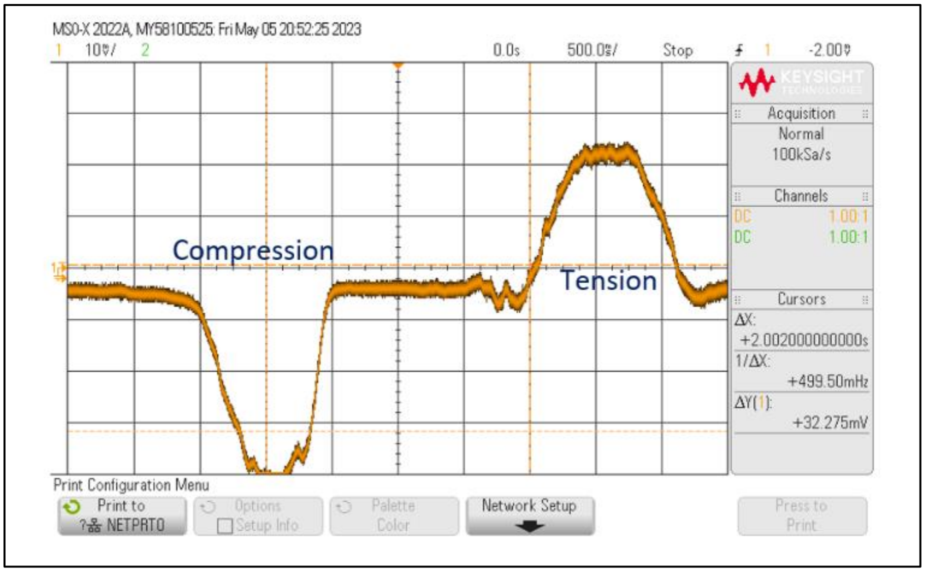


Figure 13. Amplified Load Cell on Oscilloscope

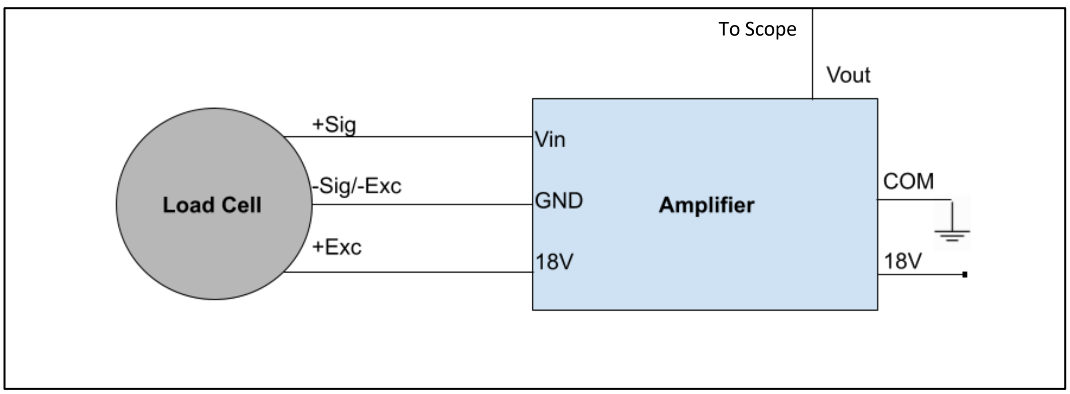


Figure 14. Connection Diagram for Simple Load Cell Test

Figure 14 shows the electrical connections necessary to perform this test. An oscilloscope was used to read the analog voltage coming from the amplifier. This voltage gets generated by the load cell and amplified to be much greater than before. Without this amplifier, the output known from the Futek calibration data (see Appendix F) for both sensors never exceeded .3mV/V in either direction for up to 440lbf. This is the expected scale of forces for a simple test like this generating mechanical strain by lightly compressing and tensing the load cell by hand. There are 8 gain-setting DIP Switches on the amplifier. Using the gain setting spreadsheet from Futek's IA100 product page, this was maximized by flipping all switches to the 1 position for a gain of 5507 V/V. The result in

Figure 13 is a voltage swing in either direction that is visible to the scope and detectable by a 12-bit ADC.

15.2.2. STRING POT TESTING

TABLE 10

STRING POT RESISTANCE MEASUREMENTS

	Resting Position Resistance (Ohms)	**Full Extension Resistance (kOhms)**
String Pot 1 - Pitch	148.8	2.592
String Pot 2 – Roll	155.1	2.598
String Pot 3 – Yaw	153.3	2.585
String Pot 4 - Throttle	152.0	2.504

These 4 sensors increase in resistance following a linear relationship to distance. The lower and upper bounds of these resistance ranges are shown in Table 10 . If configured as a voltage divider off an Arduino 5V power rail, these sensors will output the following DC voltages as measured by a multimeter.

TABLE 11

STRING POT VOLTAGE MEASUREMENTS

VCC = 5.04V	**Resting Position Voltage (mV)**	**Full Extension Voltage (V)**
String Pot 1 - Pitch	36.4	5.04
String Pot 2 – Roll	42.1	4.96

String Pot 3 – Yaw	47.1	4.98
String Pot 4 - Throttle	43.9	4.97

All these voltages are within the safe range for the ADC. However, the differences in the sensors should be accounted for in software later. Since the Natilus control column linkages and Iron Bird is not yet built, these sensors would perform better if used in tandem with a look-up-table. After the position and max travel distance of each sensor is set and finalized and the sensors are mounted, it will be simple to create this table by collecting voltage and distance datapoints while it operates, converting those voltages to digital values, and then writing the tuned/desired digital value in the table. However, this is outside of the scope for this project.

15.2.3. +/-5V TO 0-5V CONVERTER TESTING

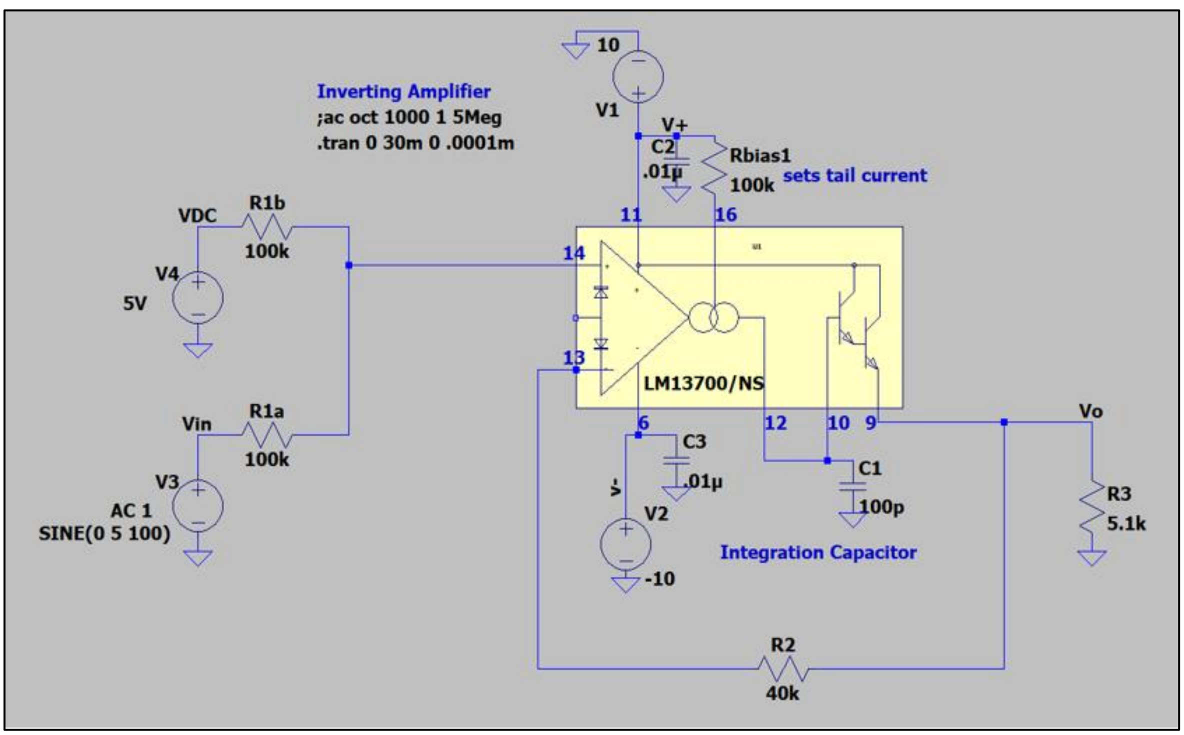


Figure 15. LTSpice Schematic of Converter Circuit.

Using an LM13700 dual transconductance amplifier with a Darlington output, this circuit was designed to take a signal in the range of +/-5V, attenuate it by .5 with respect to GND, and then shift it up by 2.5V. This creates a 0-5V signal from the previous one. It also works to shift/scale analog voltages (-5V becomes 0V, 0V becomes 2.5V, 2V becomes 3.5V, etc.).

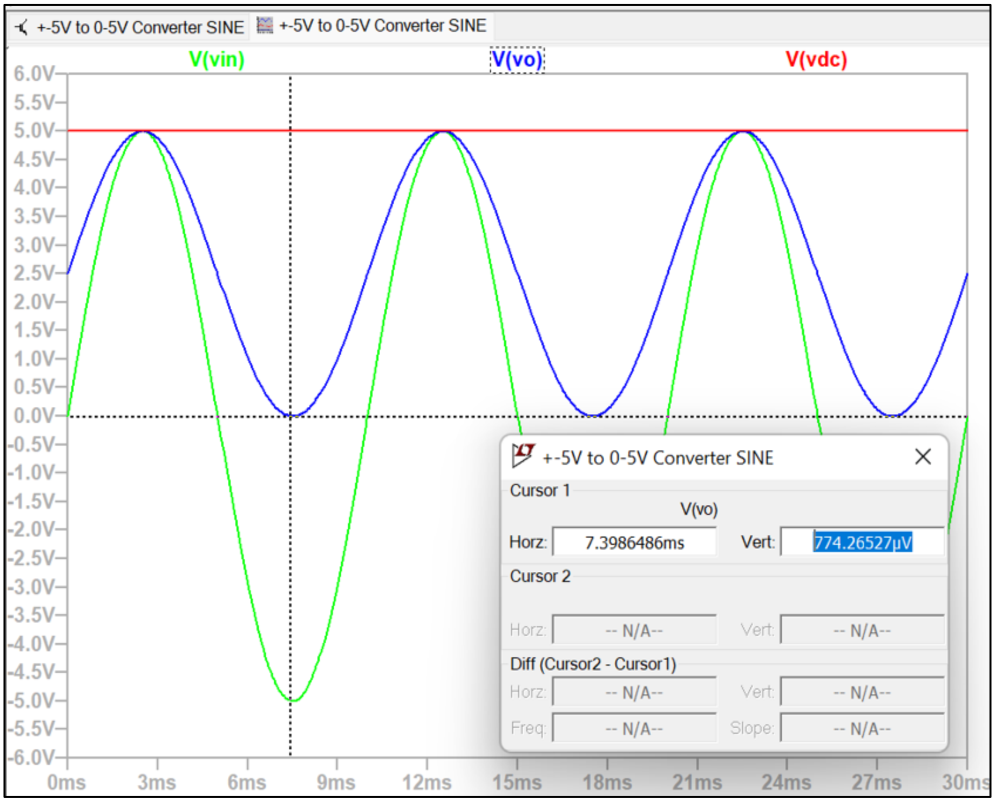


Figure 16. LTSpice Simulation of Converter Circuit

In LTSpice, the circuit simulated as expected. Never peaking above 5V or dropping below 0V. There was found to be some flexibility in the component value for R2, but 40K seemed to perform the best. An additional discovery was that changing the ratio of R1a and R1b slightly can help increase the distance from 0V and 5V the signal range sits at, giving the signal more breathing room. This can be fine-tuned if the real-world version outputs something slightly above or below the desired range.

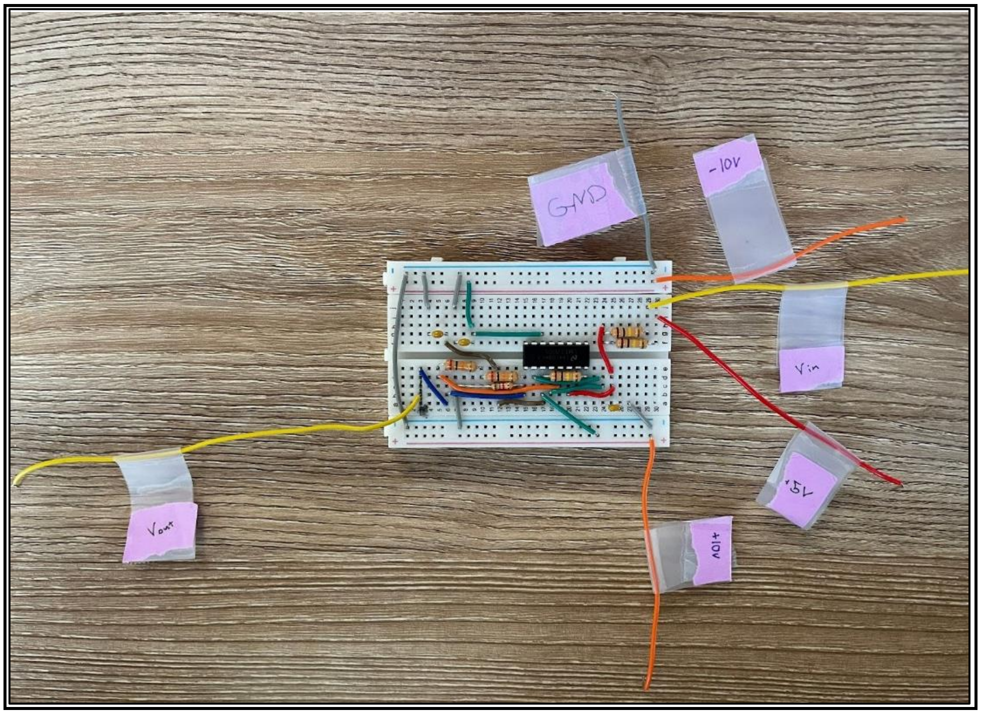


Figure 17. Converter Design Implementation

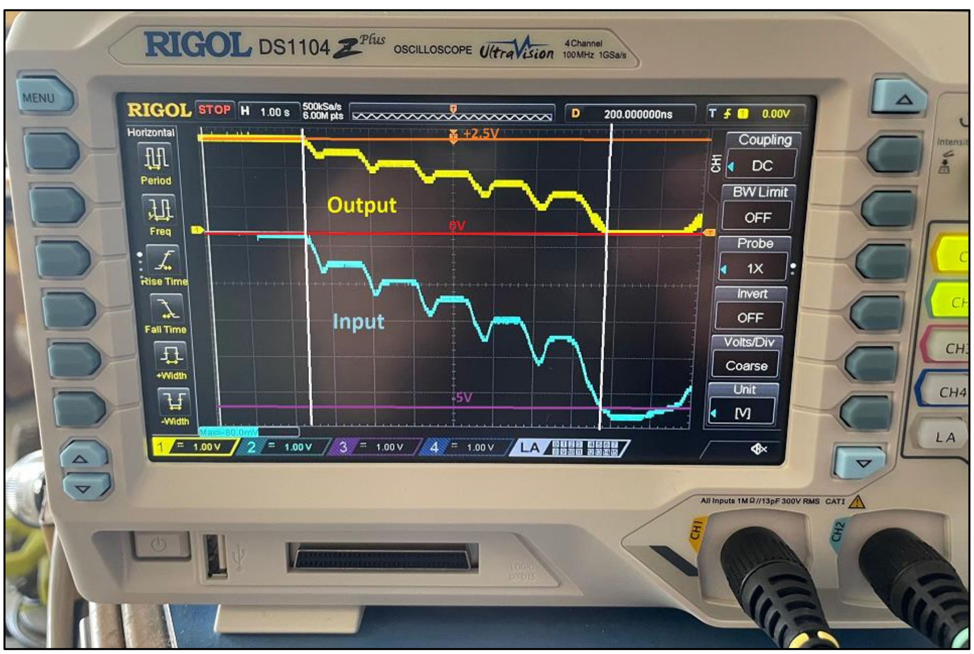


Figure 18. Converter Output Verification

The converter performed as expected, translating a "+/- 5V" sweep into a "0 to 5V" sweep. This is necessary to maximize the precision at the 12-bit ADC input of the dev board, which will be performing 5V (value from 0 to 4096) analog voltage conversions. The converter also acts as protection for the dev board analog inputs, as input voltages beyond the range of +/-5V don't generate outputs beyond 0-5V (unless the LM13700's max voltage is exceeded, in which case the circuit won't function properly anymore). This attenuation of .5 of the original value along with the shifting of the signal up by 2.5V will be necessary to read this sensor value accurately from an Arduino with as little software modification of the values as possible.

15.2.4. DEVELOPMENT BOARD TESTING

Figure 19 shows the Arduino Uno accurately reading in analog voltages and converting them to digital voltages. The digital value was then further converted back to a voltage and an angle. Since this test was performed with a regular 5kOhm rotary potentiometer the angle range was 0-270 degrees or +-135 degrees from the middle of range.

```
-----------------------------------------
POT VALUE [1023, 0]
1020

POT VOLTAGE (millivolts) [5000, 0]
4985

POT ANGLE (degrees from vertical) [-135, 135]
-134
```

Figure 19. ADC Readout in Arduino Serial Monitor

This confirms that the Arduino, its analog inputs, and its on-board ADC are operational.

15.3. INTEGRATION TESTING

To evaluate the tension and compression responses of the load cell, additional hardware was obtained. Threaded rod ends for the load cells were used to simply the process of applying known loads. A benchtop vice and several known weights were also necessary. This testing was performed in parallel with the software development and occurred at several locations:

1. The Natilus hangar at Brown Field Municipal Airport (SDM).
2. The Cal Poly electrical engineering department's student project lab.
3. The Natilus office in downtown SD.
4. An apartment in San Luis Obispo with ample workspace.

TABLE 12

INTEGRATION TESTING PLAN

Integration Tests	
Load Cell Sensors to Amplifier/Signal Conditioning to Development Board	Connect the sensor to the signal processing stage and amplifiers. Connect the signal processing stage to an analog input of the dev board. Convert this analog input to an ADC value. Using the dev board's IDE, confirm that the desired ADC values are being converted. Test the calibration process of the sensor and test with a known load.
String POT Sensors to Development Board to MATLAB	Connect the sensor in voltage divider configuration. Connect the dev board to MATLAB. Confirm that the desired ADC values are being converted to the necessary values for use in MATLAB and are readable in MATLAB. Use known distances of 0-5" and confirm.

15.3.1. SINGLE LOAD CELL – SIGNAL CONDITIONING – DEV. BOARD

Initial testing of the sensor demonstrated that the range of outputs was in the detectable range for the Arduino. By connecting the circuit as shown in Figure 20, analog voltages can be read into the ADC and converted to digital values.

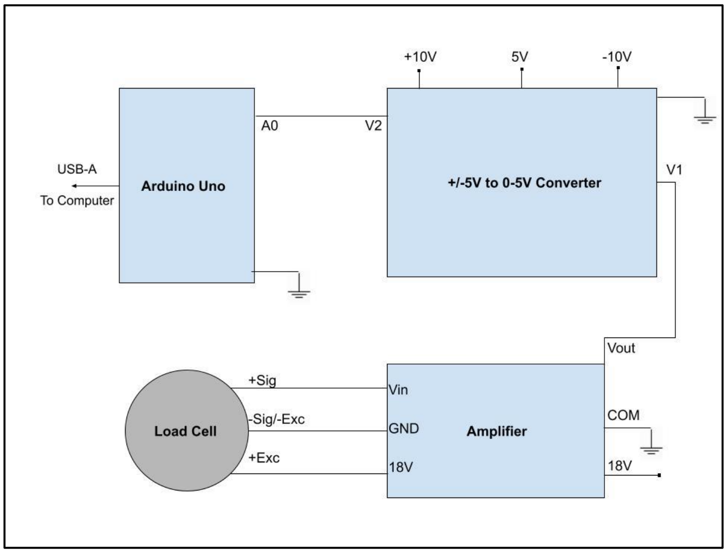


Figure 20. Single Load Cell Test Diagram

Figure 21. Known Load Test

These digital values can be shifted in software by one constant and scaled by another to read out accurate data. The data value of the load cell when at rest is used as the offset to "zero" the sensor. Scaling the values to a proper force reading will require a known load. Natilus does have a set of calibrated weights that can be used for this eventually, but for the scope of this project, exact calibrations are less important than a confirmation that the process to calibrate the sensor works. Using a plate weight that weights roughly 5lbs, the sensor was placed under tension using the apparatus in Figure 21. The sensor was zeroed before the weight was added and the correct scaling constant was found by dividing the desired reading by the current value. As shown in Figure 22, the load cell under tension was successfully scalable to 5lbs.

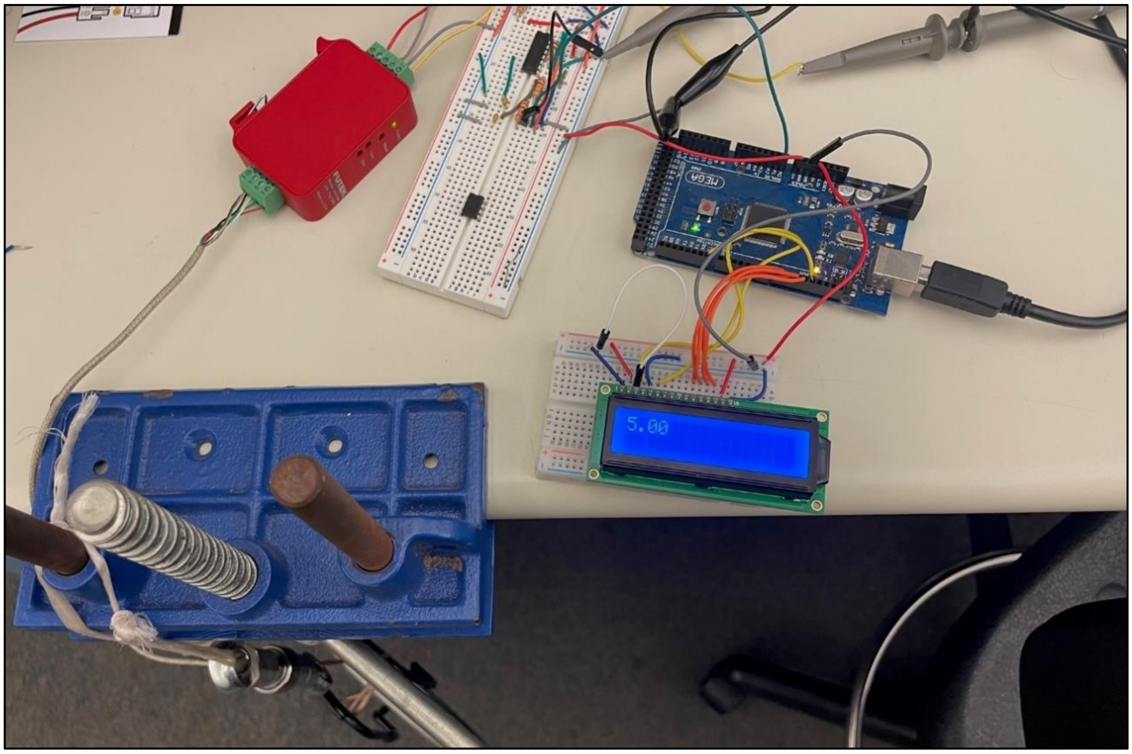


Figure 22. Single Load Cell Tension Test

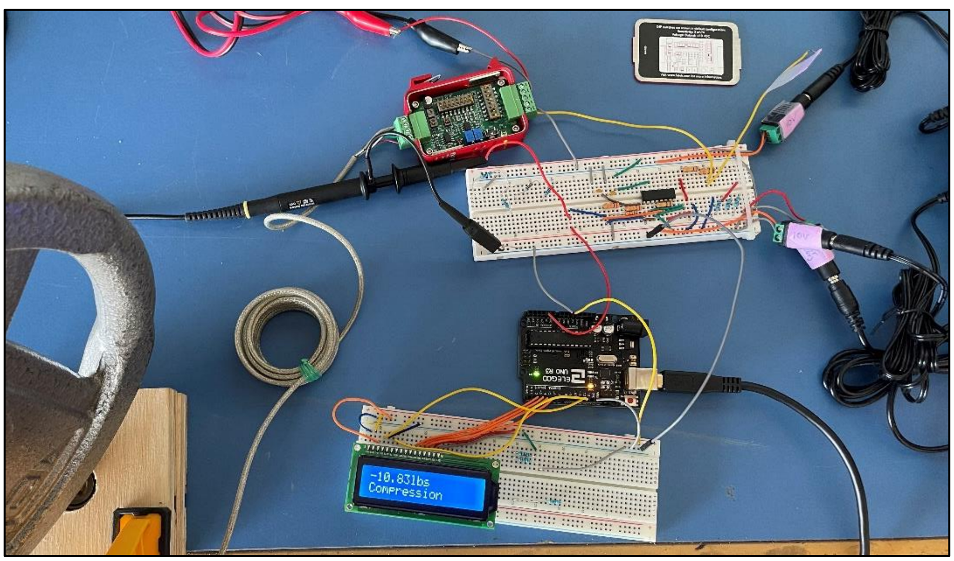


Figure 23. Single Load Cell Compression Test

Under compression, the sensor is similarly calibratable. This is difficult to do without an in-line apparatus to ensure perfect transfer of force along the vertical axis. Even so, the system was able to accurately read the force imparted, this time by a 10.5lb weight (approximated). Figure 23 above shows a slight overshoot of the desired value after scaling in software, but such a small difference in precision is negligible for the scope of this project as the minimum requirement was to be accurate within .5lb. This testing session was in a different location full of electrical equipment and experienced much more noise than anticipated. The result of this was fluctuations in the scaled value in the range of +/-.35 lb. The noise sensitivity of this system is a weakness that was first discovered during this test. See the “Discussion of Results” for suggestions on mitigating this effect as well as a solution to any non-linearity in the sensor output.

15.3.2. DUAL LOAD CELLS – SIGNAL CONDITIONING – DEV. BOARD (END-TO-END)

This test was a continuation of the previous one. Its purpose was to attempt running two load cells in parallel connected to the same power and ground. The diagram in Figure 24 shows how this was connected.

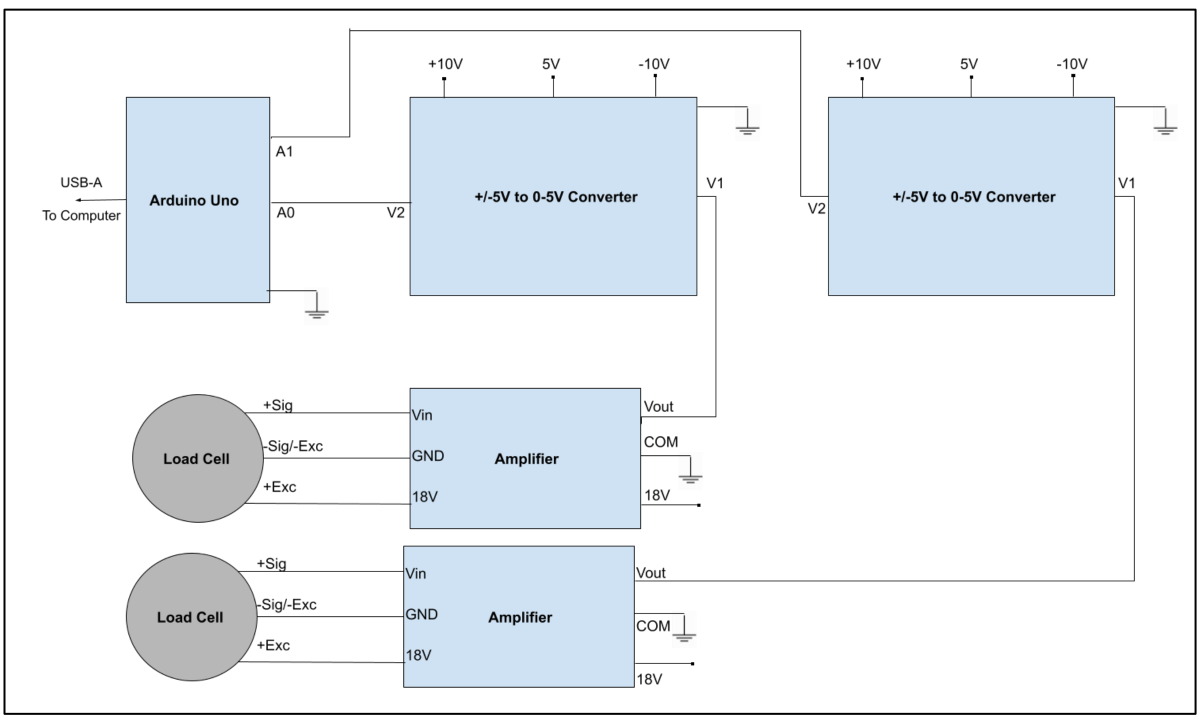


Figure 24. Dual Load Cell Test Diagram

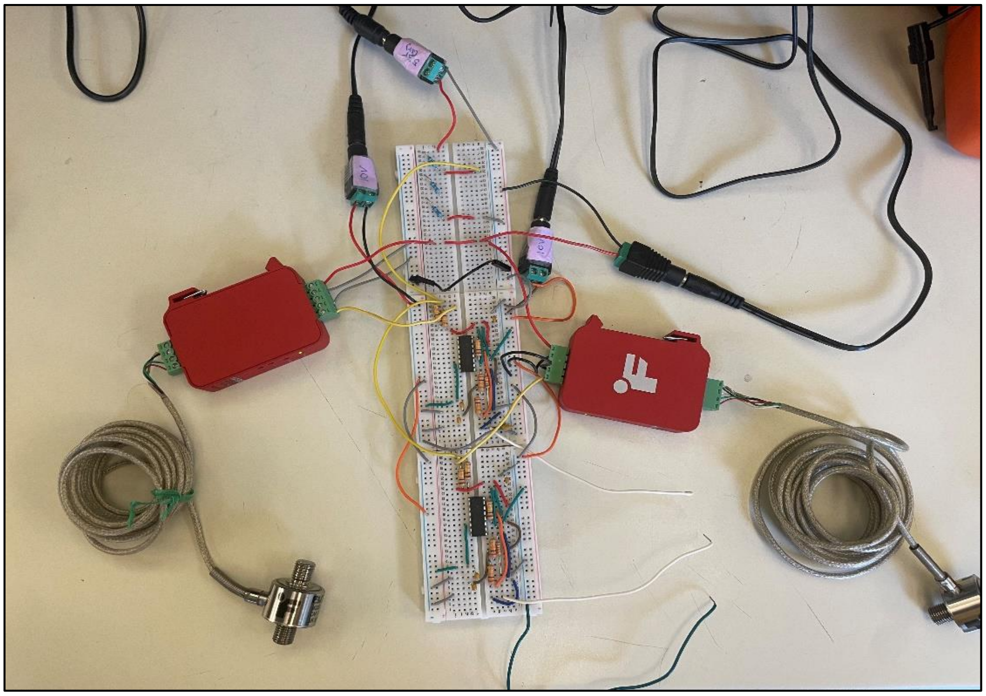


Figure 25. Dual Load Cell Test

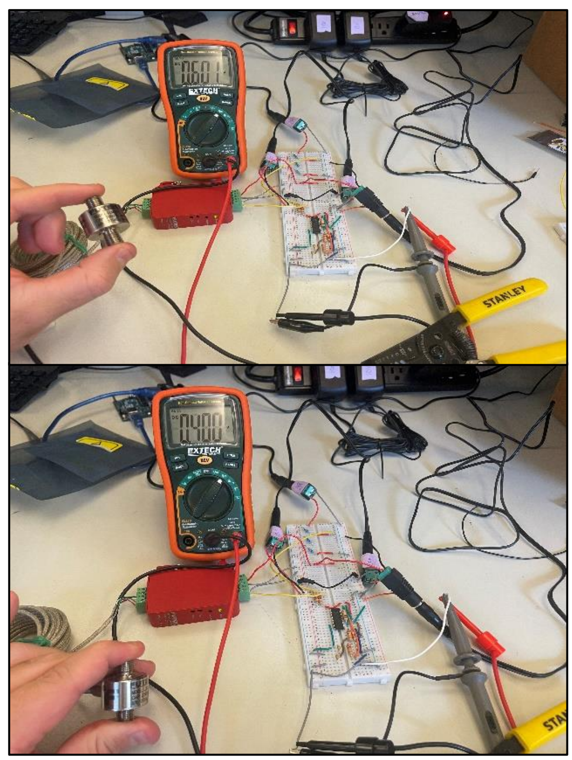


Figure 26. Dual Load Cell Multimeter Result

Figure 25 contains the fully configured hardware for the dual load cell test. A significant increase in system noise was observed during this test. While breadboards are notorious for not handling noise well, the source of the noise was likely a combination of factors. Figure 27 shows the oscilloscope capture of the signal output from one of the two load cells. As they were connected to the same power rails and ground, the noise here is representative of the noise observed on both outputs. A signal with a peak-to-peak voltage greater than 3V was present that did not appear during the single load cell testing. The main differences between the two tests were the connection of another load cell, amplifier, and voltage converter circuit to the same power rails ground, as well as the overall location of the test. However, while the AC voltages of the output are not what was expected, the DC component from Figure 26 was shown to decrease when compressed by approximately 200mV linearly. The at rest value should have been 2.5V, but this behavior is otherwise close to what we would expect. This would hint that the noise is also affecting the voltage converter stage of the system.

Figure 27. Dual Load Cell Noise Scope Capture

The previous test took place in the Natilus hangar, away from sources of noise like power lines, fans, computers, and lights. This test was conducted in Cal Poly's Electrical Engineering Student Project Lab. The wires and breadboards used for this test were unshielded and very susceptible to noise. Due to the large amplitude of the noise signal, it is likely that the noise at 177.9kHz was being introduced before the amplification stage by one or several of the electronic devices in the student project lab.

An additional possibility is that the cheaper power supplies for the circuit failed to provide clean power to the system. The same power supplies were used in the single load cell test except for the 18V supply for the load cell amplifier. This was tested by changing back to a benchtop variable power supply to see if this improved the noise. Figure 28 shows that the DC voltage and current were within the operating specs of the amplifier. Additionally, this power was confirmed to be clean by connecting it up to the oscilloscope.

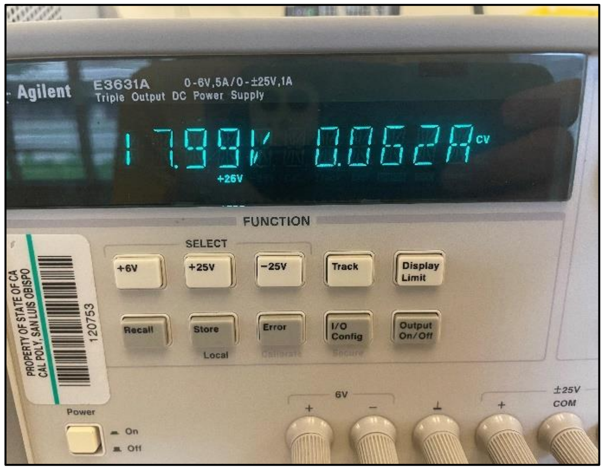


Figure 28. Load Cell Amplifier Power

It is also worth noting that unshielded wires and breadboards can act like an antenna picking up noise from the surrounding sources or propagating signals. The observed noise was in the low frequency range of the radio spectrum, so it is entirely plausible that a nearby source was present considering the test location in the Electrical Engineering building. Regardless, this introduction of noise to the system revealed a severe weakness in the design. Since the functionality of the system is conditional, revisions will be necessary before the third load cell is eventually ordered and the installation of the system into the Natilus Iron Bird takes place. However, for the scope of this project, this was a valuable test that gave much insight into some critical weak points in the design.

The potential for these weak points was overlooked for this iteration of the project since the system would not be going into an actual aircraft, but protection against noise will need to become an immediate requirement for the next round of testing. However, this is outside the scope of this project. For further analysis and proposed solutions see "Discussion of Results".

15.3.3. All 4 STRING POTS – DEV. BOARD

The string pots were each assessed by setting them up in voltage divider configuration with the sensor outputs running to Analog Inputs 0-3 on the Arduino. Before data can be sent to MATLAB for use with the simulator, it must be collected properly by the dev board. Figure 29 shows the test setup and Figure 30 shows the Arduino serial plotter readout.

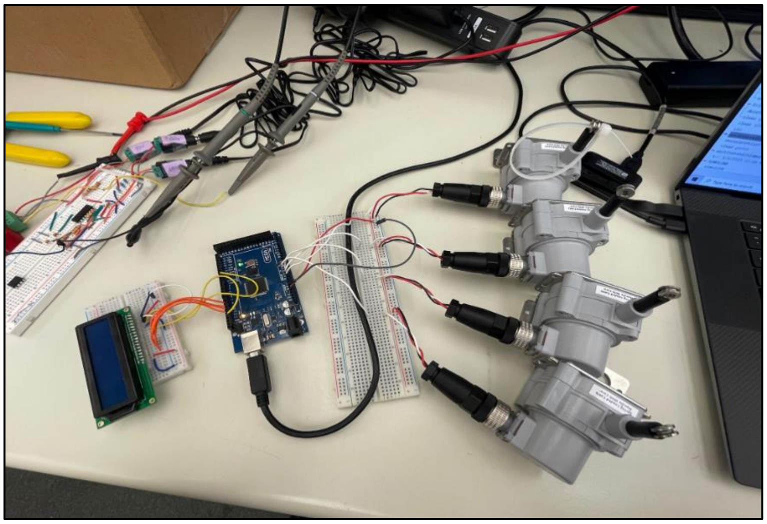


Figure 29. String POT Dev Board Testing

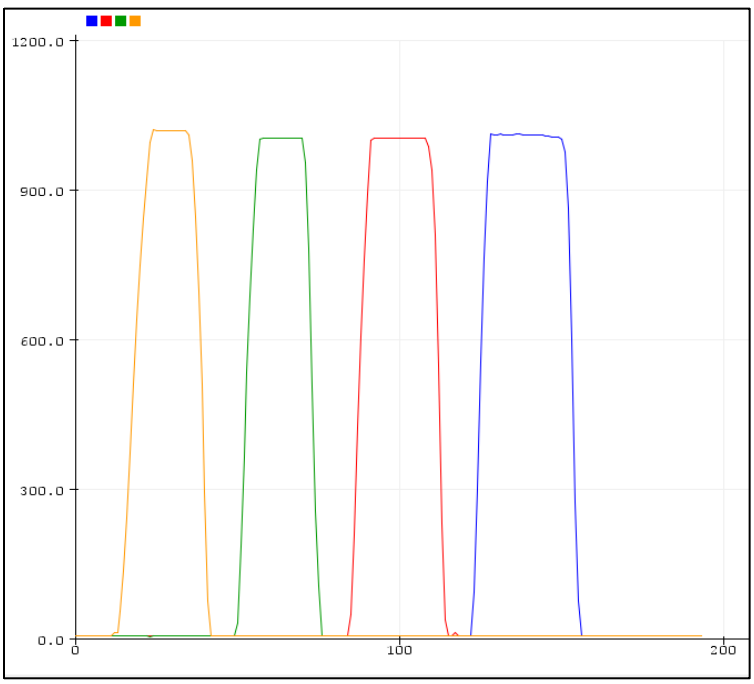


Figure 30. String POT Serial Plotter

Only the first string pot (yellow in Figure 30) went all the way up to a digital value of 1023. The rest all fell short by no greater than twenty digital values. However, this is not a concern since the max travel of these sensors is as shown in Table 13. While the design of the linkages that determine these values is still being completed, there is no notable change anticipated. The string pots used for this test have a maximum travel of twelve inches, so by not utilizing the full range of the sensors the difference in digital value ranges generated by each sensor is not a critical consideration.

TABLE 13

STRING POTENTIOMETER MAXIMUM EXPECTED TRAVELS

STRING POTENTIOMETER	MAXIMUM EXPECTED TRAVEL
Pitch	4.75”
Roll	4.5”
Yaw	1.75”
Throttle	4.75”

This test demonstrated that the sensors can be read into the Arduino or similar dev board reliably over the necessary ranges of position sensing the four desired parameters.

15.3.4. All 4 STRING POTS – DEV. BOARD – MATLAB (END-TO-END)

Serial communication was used to send data from the Arduino board to MATLAB (See Appendix C). This method proved to be reliable during initial testing. Figure 31 shows the MATLAB Simulink scope capture from sending one potentiometer value from the Arduino to all four of the commands: pitch, roll, yaw, and throttle. Sending the four potentiometer values using comma-separated serial data was then attempted. This required MATLAB to split the data and then send the four data variables to their respective command parameters in the sim. Figure 32 shows these separate digital value curves generated by all four position sensors over a 20-sec simulation. For these tests the Baud Rate was configured to 9600.

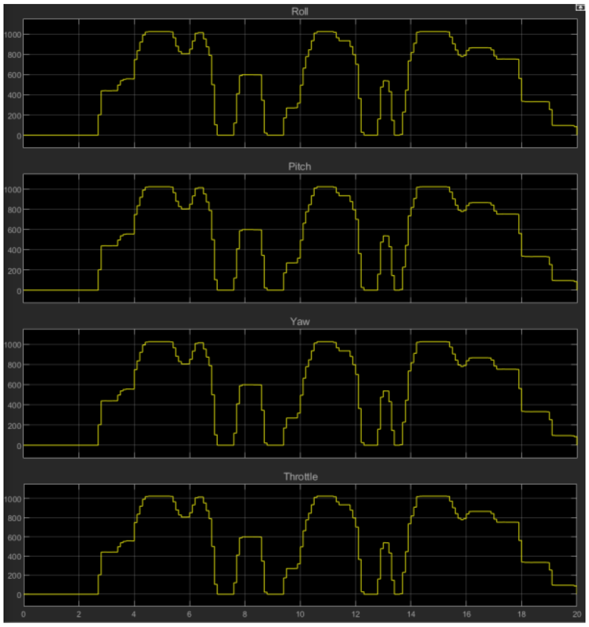


Figure 31. Single POT Simulink Scope

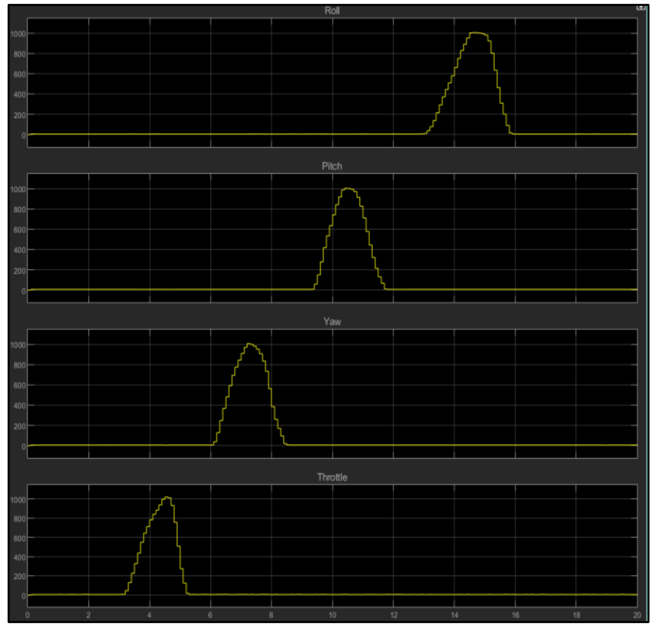


Figure 32. Quad POT Simulink Scope

This end-to-end test was successful as the MATLAB files this data was processed by connect directly to the Natilus Proprietary Sim. Figure 33 shows another plot generated by a simple MATLAB script outside of the Natilus Sim that gathers the data and plots it without all the control systems and additional aircraft specific files (See Appendix D).

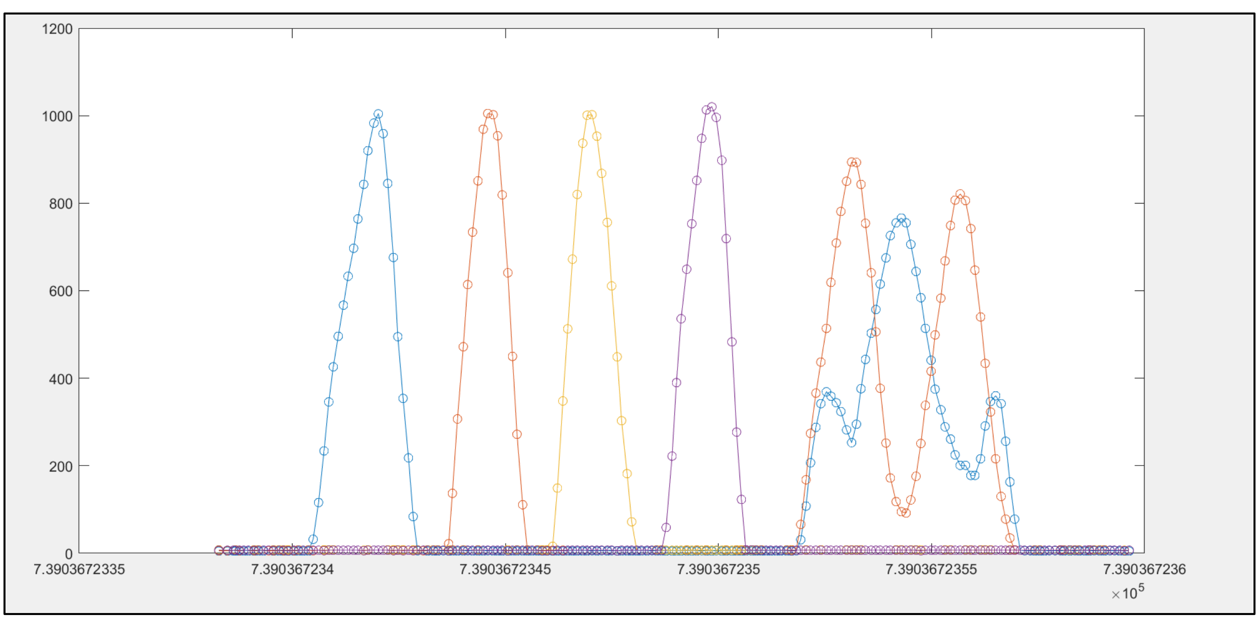


Figure 33. Quad POT MATLAB Simultaneous Travel

15.4. DISCUSSION OF RESULTS

The goal of this project was to take the first big step towards designing sensor systems that can retrieve position and force data from the Natilus Iron Bird. Within that scope, this project was an enormous success.

The end-to-end test for the load cells working in tandem did not yield the desired results, but this attempt can still be considered successful data collection. The testing was valuable because it revealed that the load cell system was less protected against noise than initially thought. Thus, the results of this test are less numerical and more qualitative. Treating this test as a learning experience, the two conclusions that can be drawn are as follows:

1. The system as currently designed is susceptible to noise from external sources.
2. Noise has a significant negative effect on the performance of the system.

The proposed solution to this problem is multifaceted. The tandem sensor test may have worked perfectly well in a separate location, but the fact that it failed provided some valuable guidance as to what can be improved. As no conclusive source for the noise was determined, testing could resume in the next iteration of this project with several changes. A good place to start would be to use shielded wires for any connections longer than a few inches, move from breadboards to PCB layouts, add a passive filter on the data signal, add AC short capacitors to help clean up the power rails and supply power from a conditioned source. Taking these steps would go a long way to clean up the signal and improve the functionality of the load cell system when running multiple in parallel.

While the dual load cell test did not work for this iteration of the design, the individual test worked quite well. This was presumably due to the test being in a separate location away from significant noise sources. The circuits were also simpler in the individual tests, having less components and wires. This would have reduced the potential for the system to pick up interference. Thus, while the force sensing aspect of this project was only a partial success from a technical perspective, the experimental learning process through the testing phase contributed to the overall purpose of this project. Now that the system's vulnerability to noise is apparent, the next iteration of this project will be more equipped to meet Natilus's need for an accurate and reliable force sensing system. Even though Natilus's priority for this project was placed on position sensing, this is still really valuable information that will help tremendously as the move towards Iron Bird HIL testing approaches.

The end-to-end test for the string potentiometer position sensors worked as designed. This was a simpler system than the load cell force sensors as it required no amplification or additional components. Additionally, the only power source necessary was the voltage from the Arduino development board. The same noise issue was not observed. Instead, clean analog voltages were converted to digital values and sent via serial communication to MATLAB. This was a success both technically and as a learning experience.

15.5. FUTURE IMPROVEMENTS

Future improvements to and iterations of this project include creating a Python visualization tool for the load cell data and finding a way to record and plot it over time. Additionally, all the improvements listed in the "Discussion of Results" section should be applied to the load cell system to reduce the noise being introduced. The system has remained modular up till the end of this project to allow for minimal upset due to any potential changes to the mechanical design of the control column linkages from Natilus. But as the aircraft's development moves forward, confirming and finalizing these distances will enable the design and implementation of shielded wire harnesses that are the correct lengths. Additional improvements and changes to the simulator will be necessary to read in the data from the additional load cell that will be added to the force sensor system. This project iteration only had the budget for 2/3 of the desired load cells, but after solving the noise issue this can be revisited later. One of the priorities for this endeavor will be moving the system to PCBs. This would improve the quality and organization of the system while allowing it to remain modular. Another improvement that may become necessary is the use of look-up-tables to correct any non-linearity in the sensors. This does not appear to be an issue with the string pots but as Natilus begins to evaluate higher system forces the mv/V of the load cells may not remain linear. All data precision could be improved by upgrading the ADC to a higher-bit module. The system will eventually be run through a TI Hercules series development board with much greater specs than the Arduino uno.

The bulk of the work going forward appears to lie with the load cell system, which was not as high of a priority for the scope of this project. Additionally, there is a clear path forward to rectify the issues that arose, demonstrating the value of the testing that was performed so far.

15.6. FUTURE TESTS

Since this system will be used primarily in the HIL Iron Bird testing, it will not be under extreme vibrational forces, but it is important to identify weak points in the system at this stage before they go onto the first flight plane later. In summation, any solder joints that are made on wires in this version of the system should be exchanged later for aircraft-approved connectors when moved to the test plane. This is far outside the scope of this project but important to note. At present, the electronics remain on breadboards as a modular prototype. The finalization of PCBs is also outside the scope of this project; however, it is a vital next step. Eventually, these vibration tests could be done by simulating the expected max vibrational forces within the aircraft and recreating them by driving around in a car or a test plane. Vibrational tables would be a more credible test for this and would potentially even provide reassuring certification for this system.

Setting up the load cell system with calibrated weights (Natilus has a set) will also be an important test later. This will allow for more meaningful and accurate data collection in the Iron Bird.

16. ENDNOTES:

[1] Natilus "Vehicles" page on their website [1]

[2] Design by Flight Control Engineer Adrian Chabursky [4]

[3] Current head of the autopilot department [4]

[4] Protected by NDA [4]

17. REFERENCES:

[1] "Vehicles," *Natilus*. https://natilus.co/vehicles/ (accessed Oct. 19, 2022).

[2] Digikey, "Products," *Digikey*. https://www.digikey.com/en/products (accessed Oct. 18, 2022).

[3] "Inline Load Cell | Tension and Compression Load Cell Application," *www.futek.com*. https://www.futek.com/store/load-cells/threaded-in-line-load-cells (accessed Oct. 19, 2022).

[4] A. Matyushev, K. Sheehy, A. Chabursky, and Y. Araya, "Instrumented Control Column Project Correspondence."

[5] "Boeing: Autonomous Systems," *Boeing.com*, 2016. https://www.boeing.com/defense/autonomous-systems/index.page

[6] "Flight Control Sensors," *LORD Corp*, May 03, 2018. https://www.lord.com/products-and-solutions/flight-control-equipment/flight-control-sensors (accessed Oct. 19, 2022).

[7] "Potentiometer as a Voltage Divider | DC Circuits | *www.allaboutcircuits.com*. https://www.allaboutcircuits.com/textbook/experiments/chpt-3/potentiometer-voltage-divider

[8] ERAU SpecialVFR, "Aircraft Systems - 02 - Flight Controls," *www.youtube.com*. https://www.youtube.com/watch?v=WhQ8Ai4fa_Q (accessed Jul. 27, 2022).

[9] "Suppliers - Northrop Grumman," *Suppliers*. https://www.northropgrumman.com/suppliers/ (accessed Oct. 19, 2022).

[10] "home | Airbus | Aerospace Pioneer," *www.airbus.com*. https://www.airbus.com/en

[11] "IAA100 Product Manual." Accessed: Jun. 12, 2023. [Online]. Available: https://eusfecomprodstgmedia.blob.core.windows.net/docs/support/IAA100ProductManual.pdf

[12] "COMMON SOURCES OF ELECTRICAL NOISE SIGNAL DISTORTED BY NOISE Sensor Solution Source Load · Torque · Pressure · Multi-Axis · Calibration · Instruments · Software How to Reduce Electrical Noise in Your System." Accessed: Jun. 12, 2023. [Online]. Available: https://eusfecomprodstgmedia.blob.core.windows.net/docs/support/how-to-reduce-electrical-noise-in-your-system.PDF

[13] "LM13700 LM13700 Dual Operational Transconductance Amplifiers With Linearizing Diodes and Buffers." Accessed: Jun. 12, 2023. [Online]. Available: https://www.ti.com/lit/ds/symlink/lm13700.pdf?ts=1686545106121

[14] "Sensor Solution Source Load · Torque · Pressure · Multi-Axis · Calibration · Instruments ·

Software." Accessed: Jun. 12, 2023. [Online]. Available:
https://media.futek.com/content/futek/files/pdf/productdrawings/fsh04009.pdf

[15] "ZeroAvia | Natilus | Partnership | ZA600 Hydrogen-Electric Engine | Kona Blended-Wing Body Cargo UAV," *ZeroAvia*.
https://www.zeroavia.com/natilus-partnership (accessed Jun. 12, 2023).

[16] Electronics tutorials, "Summing Amplifier is an Op-amp Voltage Adder," *Basic Electronics Tutorials*, Feb. 2019.
https://www.electronics-tutorials.ws/opamp/opamp_4.html

APPENDIX A

FMEA: POTENTIAL FAILURE MODE AND EFFECTS ANALYSIS

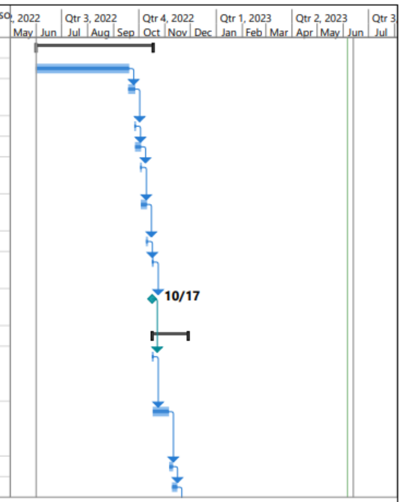
Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	Sev	Potential Cause(s)/ Mechanism(s) of Failure	Prob	Current Design Controls	Det	RPN	Recommended Action(s)	Responsibility & Target Completion Date
Load Cell	Mechanical Failure,	Pushrod breaks, Inaccurate Pilot Input Data,	8	System max force calculations were wrong	1	Pushrods, Control Surfaces	1	8	Oversize Load Cells so that failure probability is reduced further	Andrew Klein, Design - Nov. 2022
	Overvoltage	Inaccurate Pilot Input Data, Electrical Damage	6	Too high a voltage supplied to excite the load cell	1	ADC, MATLAB Variable Monitoring, Simulator	1	6		
	Loss of Excitation	Inaccurate Pilot Input Data	6	Excitation voltage is lost, Damage to Amplifier	1	AmplifierADC, MATLAB Variable Monitoring, Simulator	1	6		
String Potentiometer	Mechanical failure,	Inaccurate Flight Control Data	8	System max travel calculations were wrong	1	ADC, MATLAB Variable Monitoring, Simulator	1	8	Oversize String POTs so that failure probability is reduced further	Andrew Klein, Design - Nov. 2022
	Overvoltage	Inaccurate Flight Control Data, Electrical Damage	6	Too high a voltage supplied to excite the string POT	1	ADC, MATLAB Variable Monitoring, Simulator	1	6		
	Loss of Voltage	Inaccurate Flight Control Data	6	Voltage is lost across the viable resistor	1	ADC, MATLAB Variable Monitoring, Simulator	1	6		
Electrical Wire - Load Cell to Amplifier	Mechanical failure,	Inaccurate Pilot Input Data	6	Severing, Work Hardeneing of Metal, Incorrect AWG	2	ADC, MATLAB Variable Monitoring, Simulator	1	12	Bundle Wires and use ductile copper wires of correct AWG	Andrew Klein, Build - Jan. 2023
Electrical Wire - Load Cell Amplifier to Voltage Converter	Mechanical failure,	Inaccurate Pilot Input Data	6	Severing, Work Hardeneing of Metal, Incorrect AWG	2	ADC, MATLAB Variable Monitoring, Simulator	1	12	Bundle Wires and use ductile copper wires of correct AWG	Andrew Klein, Build - Jan. 2023
Electrical Wire - Voltage Converter to Development Board ADC	Mechanical failure,	Inaccurate Pilot Input Data	6	Severing, Work Hardeneing of Metal, Incorrect AWG	2	ADC, MATLAB Variable Monitoring, Simulator	1	12	Bundle Wires and use ductile copper wires of correct AWG	Andrew Klein, Build - Jan. 2023
Electrical Wire - String Potentiometer to Development Board ADC	Mechanical failure,	Inaccurate Flight Control Data	6	Severing, Work Hardeneing of Metal, Incorrect AWG	2	ADC, MATLAB Variable Monitoring, Simulator	1	12	Bundle Wires and use ductile copper wires of correct AWG	Andrew Klein, Build - Jan. 2023
Electrical Wire -Development Board to Computer	Mechanical failure,	Inaccurate Flight Control Data	6	Severing, Work Hardeneing of Metal, Incorrect AWG	2	ADC, MATLAB Variable Monitoring, Simulator	1	12	Bundle Wires and use ductile copper wires of correct AWG	Andrew Klein, Build - Jan. 2023
Load Cell Amplifier	Overvoltage	Inaccurate Flight Control Data	7	Too high a voltage supplied to amplifier	2	ADC, MATLAB Variable Monitoring, Simulator	1	14	Source high quality power supplies for testing	Andrew Klein, Design - Nov. 2022
Converter	Overvoltage	Inaccurate Flight Control Data	7	Too high a voltage supplied to converter	2	ADC, MATLAB Variable Monitoring,	1	14	Source high quality power supplies for	Andrew Klein, Design - Nov. 2022
Development Board	Overvoltage	Inaccurate Flight Control Data	7	Too high a voltage supplied to development board	2	MATLAB Variable Monitoring, Simulator	1	14	Source high quality power supplies for testing	Andrew Klein, Design - Nov. 2022
Development Board Data Retrieval Code	Data Error	Inaccurate Flight Control Data	7	Bugs in code, exceptions	1	Simulator, MATLAB Variable Monitoring	3	21	Simpllify and thoroughly test code	Andrew Klein, Build - Jan. 2023

MATLAB	Data Error	Inaccurate Flight Control Data	7	Bugs in code, exceptions, Connection issue, toolbox, driver error	1	Simulator, MATLAB Variable Monitoring	3	21	Simpllify and thoroughly test data Integration	Andrew Klein, Build - Jan. 2023
Connectors	Mechanical Failure	Inaccurate Flight Control Data, Inaccurate Pilot Input Data	8	Pin Damage, Crushing Force, Vibration Damage	1	ADC, MATLAB Variable Monitoring, Simulator	1	8	Source sealed connectors so that failure probability is reduced further	Andrew Klein, Design - Nov. 2022

APPENDIX B

GANT CHART AND SCHEDULE COMPLETION BREAKDOWN

ID		Task Mode	Task Name	Duration	Start	Finish	Predece	Successo
1	✓		**Define**	**99 days**	**Wed 6/1/22**	**Mon 10/17/2**		
2	✓		Identify Produ	78 days	Wed 6/1/22	Sun 9/18/22		3
3	✓		Get Advisor Approval	5 days	Mon 9/19/22	Sun 9/25/22	2	4
4	✓		Abstract	1 day	Mon 9/26/22	Mon 9/26/22	3	5
5	✓		NABC	4 days	Tue 9/27/22	Sun 10/2/22	4	6
6	✓		Marketing Need	1 day	Mon 10/3/22	Mon 10/3/22	5	7
7	✓		Design Requirement:	4 days	Tue 10/4/22	Sun 10/9/22	6	8
8	✓		Test Plan	1 day	Mon 10/10/2	Mon 10/10/2	7	9
9	✓		FMEA Submission	1 day	Mon 10/17/22	Mon 10/17/22	8	10
10	✓		First Pass Senior	0 days	Mon 10/17/22	Mon 10/17/22	9	12
11	✓		**Design**	**31 days**	**Mon 10/17/2**	**Mon 11/28/2**		
12	✓		Functional Decompositic lv 0, 1	1 day	Mon 10/17/22	Mon 10/17/22	10	13
13	✓		Functional Decompositic lv 2	14 days	Tue 10/18/22	Fri 11/4/22	12	14
14	✓		Top Level Des	3 days	Mon 11/7/22	Wed 11/9/22	13	15
15	✓		Sensor Sourci	3 days	Thu 11/10/2	Mon 11/14/2	14	16

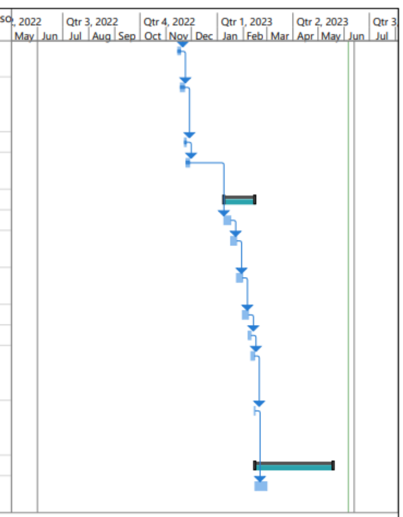


Project: SeniorProjectSchedule_
Date: Tue 6/6/23

Task	Inactive Summary	External Tasks
Split	Manual Task	External Milestone
Milestone	Duration-only	Deadline
Summary	Manual Summary Rollup	Progress
Project Summary	Manual Summary	Manual Progress
Inactive Task	Start-only	
Inactive Milestone	Finish-only	

Page 1

ID		Task Mode	Task Name	Duration	Start	Finish	Predece	Successo
16	✓		Signal Processing	3 days	Tue 11/15/22	Thu 11/17/22	15	17
17	✓		IC and Microprocess Sourcing	3 days	Fri 11/18/22	Tue 11/22/22	16	18
18	✓		Code Flowcha	2 days	Wed 11/23/2	Thu 11/24/22	17	19
19	✓		Advisor Design	2 days	Fri 11/25/22	Mon 11/28/22	18	21
20			**Build**	**27 days?**	Mon 1/9/23	Tue 2/14/23		
21			Amplifier Buil	6 days	Mon 1/9/23	Mon 1/16/23	19	22
22			Voltage Level Shifter	5 days	Tue 1/17/23	Mon 1/23/23	21	23
23			Microprocess Coding	5 days	Tue 1/24/23	Mon 1/30/23	22	24
24			MATLAB Codi	5 days	Tue 1/31/23	Mon 2/6/23	23	25
25			Power Bus Bu	3 days	Tue 2/7/23	Thu 2/9/23	24	26
26			Build Test Apparatus for Load	2 days	Fri 2/10/23	Mon 2/13/23	25	27
27			Second Advisor Design/Build	1 day	Tue 2/14/23	Tue 2/14/23	26	29
28			**Validate**	**67 days**	**Wed 2/15/2**	Thu 5/18/23		
29			Component Testing	2 wks	Wed 2/15/23	Tue 2/28/23	27	

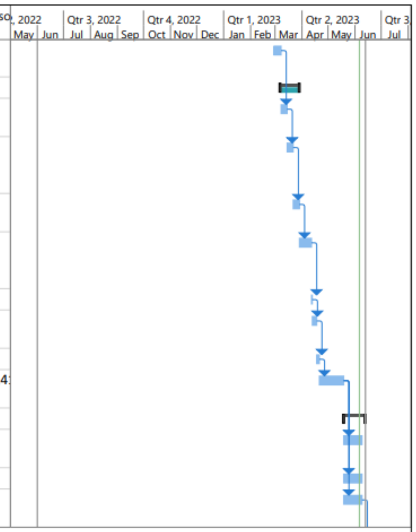


Project: SeniorProjectSchedule_
Date: Tue 6/6/23

Task	Inactive Summary	External Tasks
Split	Manual Task	External Milestone
Milestone	Duration-only	Deadline
Summary	Manual Summary Rollup	Progress
Project Summary	Manual Summary	Manual Progress
Inactive Task	Start-only	
Inactive Milestone	Finish-only	

Page 2

ID		Task Mode	Task Name	Duration	Start	Finish	Predece	Successo
30			Integration Testing	1.2 wks	Tue 2/28/23	Tue 3/7/23		32
31			**System Testi**	**16 days**	**Tue 3/7/23**	**Tue 3/28/23**		
32			Load Cell Under	1 wk	Wed 3/8/23	Tue 3/14/23	30	33
33			Load Cell Under Compressi	1 wk	Wed 3/15/23	Tue 3/21/23	32	34
34			Potentiom Testing	1 wk	Wed 3/22/23	Tue 3/28/23	33	35
35			Troubleshoot and Improvement	2 wks	Wed 3/29/23	Tue 4/11/23	34	36
36			Vibration Tes	1 day	Wed 4/12/23	Wed 4/12/23	35	37
37			Advisor Feedback	3 days	Thu 4/13/23	Mon 4/17/23	36	38
38			Natilus Feedb	3 days	Tue 4/18/23	Thu 4/20/23	37	39
39			Improvement and	1 mon	Fri 4/21/23	Thu 5/18/23	38	42,43,4
40			**Release**	**17 days**	**Fri 5/19/23**	**Mon 6/12/2**		
41			Final Draft Senior	3 wks	Fri 5/19/23	Thu 6/8/23	39	
42			Create Poster	3 wks	Fri 5/19/23	Thu 6/8/23	39	
43			Prepare Presentation	3 wks	Fri 5/19/23	Thu 6/8/23	39	44

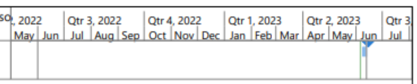


Project: SeniorProjectSchedule_
Date: Tue 6/6/23

- Task
- Split
- Milestone
- Summary
- Project Summary
- Inactive Task
- Inactive Milestone
- Inactive Summary
- Manual Task
- Duration-only
- Manual Summary Rollup
- Manual Summary
- Start-only
- Finish-only
- External Tasks
- External Milestone
- Deadline
- Progress
- Manual Progress

Page 3

ID		Task Mode	Task Name	Duration	Start	Finish	Predece	Successo
44			Senior Project Expo	2 days	Fri 6/9/23	Mon 6/12/23	43	



Project: SeniorProjectSchedule_
Date: Tue 6/6/23

- Task
- Split
- Milestone
- Summary
- Project Summary
- Inactive Task
- Inactive Milestone
- Inactive Summary
- Manual Task
- Duration-only
- Manual Summary Rollup
- Manual Summary
- Start-only
- Finish-only
- External Tasks
- External Milestone
- Deadline
- Progress
- Manual Progress

Page 4

APPENDIX C

SERIAL COMMUNICATION CODE/SCRIPTS

ARDUINO SERIAL SENDING

```
/*
  Serial Test FOR 4 SENSORS
*/

int sensorPin0 = A0;  // select the input 0 pin
int sensorPin1 = A1;  // select the input 1 pin
int sensorPin2 = A2;  // select the input 2 pin
int sensorPin3 = A3;  // select the input 3 pin

float sensorValue0 = 0;  // variable to store the value coming from sensor 1
float sensorValue1 = 0;  // variable to store the value coming from sensor 2
int sensorValue2 = 0;    // variable to store the value coming from sensor 3
int sensorValue3 = 0;    // variable to store the value coming from sensor 4

void setup() {
  // initialize serial port
  Serial.begin(9600);
}

void loop() {
  // read from the analog pins and convert
  sensorValue0 = analogRead(sensorPin0);
  sensorValue1 = analogRead(sensorPin1);
  sensorValue2 = analogRead(sensorPin2);
  sensorValue3 = analogRead(sensorPin3);

  // send digital values to the serial port as "comma-separated" data
  Serial.print(sensorValue0);
  Serial.print(",");
  Serial.println(sensorValue1);
  Serial.print(",");
  Serial.print(sensorValue2);
  Serial.print(",");
  Serial.println(sensorValue3);

  // optional delay (may improve performance)
  // delay(100);
}
```

```
%-------------------------------------------------------
% Close and clear all open serial ports
if ~isempty(instrfind)
    fclose(instrfind);
    delete(instrfind);
    clear instrfind;
end

% List available serial ports
serialPorts = seriallist;

% Clear connections to all available serial ports
for i = 1:length(serialPorts)
    try
        % Create a serial port object
        s = serial(serialPorts{i});
        % Clear the port if it is open
        if strcmp(s.Status, 'open')
            flushinput(s);
            flushoutput(s);
        end
        % Delete the serial port object
        delete(s);
        clear s;

        disp(['Cleared connection to serial port: ' serialPorts{i}]);
    catch
        disp(['Failed to clear connection to serial port: ' serialPorts{i}]);
```

```
    end
end

%------------------------------------------------------------------------------
% Serial Test For 4 String Potentiometers

% run for 20 seconds
total_run_time = 20;

% plot Setup
figure;
h1 = plot(NaN, NaN, '-o'); % create empty plot for data 1
hold on; % enable plot stacking
h2 = plot(NaN, NaN, '-o'); % create empty plot for data 2
h3 = plot(NaN, NaN, '-o'); % create empty plot for data 3
h4 = plot(NaN, NaN, '-o'); % create empty plot for data 4

% empty variable to hold time stamps
time_stamps = [];

% select serial port
out.socket = serial('COM6');

% configure serial port
set(out.socket, 'BaudRate', 9600);
fopen(out.socket);
tic;

% initialize the result variable
result = [];
```

```
while true
    % read data from serial port and update result variable
    serialData = fscanf(out.socket);
    data = str2double(strsplit(serialData, ','));
    result = [result; data];  % Append new data to the result variable

    % append current time stamp to time_stamps vector
    time_stamps = [time_stamps; datetime('now')];

    % convert time_stamps to numeric format
    xData = datenum(time_stamps);

    % update the plots
    set(h1, 'XData', xData, 'YData', result(:,1)');
    set(h2, 'XData', xData, 'YData', result(:,2)');
    set(h3, 'XData', xData, 'YData', result(:,3)');
    set(h4, 'XData', xData, 'YData', result(:,4)');
    drawnow;

    % check elapsed time and break out of loop if necessary
    if toc > total_run_time
        disp('20 sec elapsed, end of data capture');
        break;
    end
end

% Close the serial port
fclose(out.socket);
```

APPENDIX D

NOTE ON NATILUS PROPRIETARY SIMULATOR

The Natilus proprietary sim is being developed by Kyle Sheehy. Due to the protections in place on this program and information surrounding it, this project report cannot include sections of or details of this simulator. This information is restricted by NDA and contains control systems, experimental vehicle information, environmental data, and other aircraft systems specific to the Natilus N38T prototype.

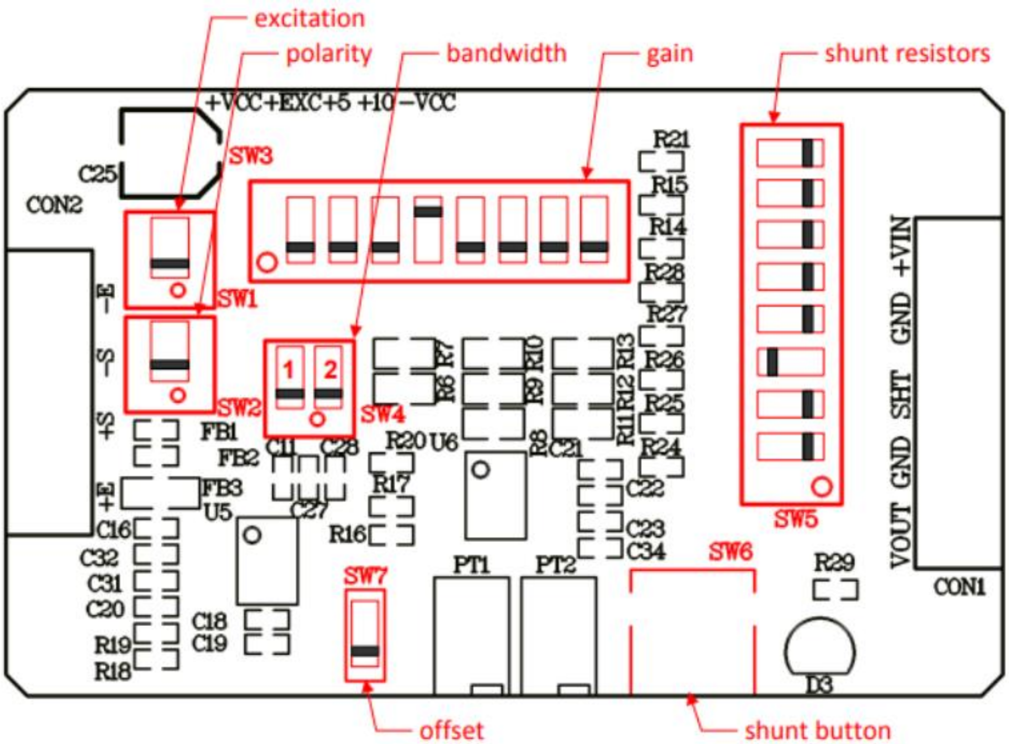
However, MATLAB script that can perform a similar process of reading in data from a serial port has been included in Appendix C. This is a simplified program flow that does not involve Simulink, but it does demonstrate the working knowledge necessary to achieve fluid serial communication.

APPENDIX E

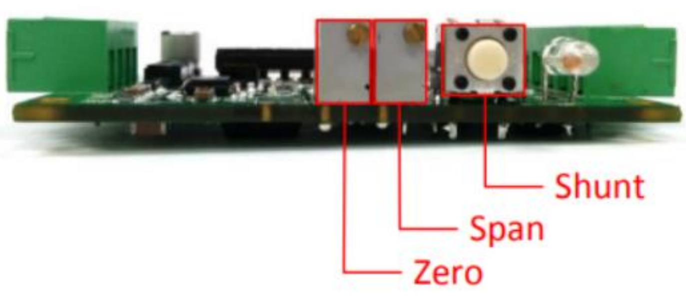
FUTEK LOAD CELL AMPLIFIER INFORMATION

(Information from REFERENCE 11; IA100 Product Manual)

SCHEMATIC



BUTTON IDENTIFICATION



Advanced Span and Zero Adjustment

Adjusting the Zero

At times, when using a signal conditioner, it is necessary to offset the zero. The IAA100 makes this simple. The zero can be adjusted approximately ± 10% of R.O. by using the potentiometer on board.

Adjusting the Span

The input jumpers vary from 0.5 mV/V to 10.0 mV/V. This allows for a large variety of input ranges. However, it sometimes happens that the rated output from the sensor is not exactly 2.0 mV/V or 3.0 mV/V. The IAA100 has a ± 10% of R.O. adjustment range so a sensor with an output close to one of the input ranges will work fine.

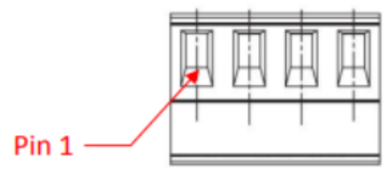
Default Settings

- Input Range: +/-2 mV/V
- Excitation Voltage: 10 VDC
- Output Range: +/-10 VDC
- Shunt: 60.4 kΩ

Connections

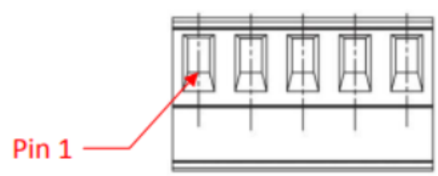
Sensor Side	
Pin	**Wiring Code**
1	+Excitation[1]
2	+Signal
3	-Signal
4	-Excitation[1]

4 Position Screw Terminal



Power Side	
Pin	**Wiring Code**
1	+Vin
2	Ground
3	Shunt
4	Ground
5	Vout

5 Position Screw Terminal



APPENDIX F

FUTEK LOAD CELL CALIBRATION DATA

FUTEK
ADVANCED SENSOR TECHNOLOGY, INC.

10 Thomas, Irvine, CA 92618 USA
Tel: (949) 465-0900

Certificate Number: 2207130050

Single Channel Item

CALIBRATION DATA

Test Temp: 72 °F (22 °C)
Relative Humidity: 32 %
Excitation: 9.99 Vdc
Input Resistance: 355 Ω
Output Resistance: 355 Ω
Zero Balance: -0.0001 mV/V

Tension

Load (lb)	Output (mV/V)	Non-Lin. Error (% R.O.)
0	0.0011	0.000
440	0.2909	-0.100
800	0.5301	-0.024
1,200	0.7938	-0.097
1,600	1.0594	-0.026
2,000	1.3244	0.000
0	0.0009	0.000

Compression

Load (lb)	Output (mV/V)	Non-Lin. Error (% R.O.)
0	0.0003	0.000
440	-0.2855	-0.321
800	-0.5237	-0.252
1,200	-0.7890	-0.127
1,600	-1.0538	-0.041
2,000	-1.3180	0.000
0	-0.0001	0.000

Last Revised: 2022.07.13 CertReg 5.6.2.0 Page 2 of 3

Sensor Solution Source
Load · Torque · Pressure · Multi-Axis · Calibration · Instruments · Software
www.futek.com

ANSI Z540-1 · ISO 17025 · ISO 9001 · ISO 13485 · U.S. Manufacturer

FUTEK
ADVANCED SENSOR TECHNOLOGY, INC.

10 Thomas, Irvine, CA 92618 USA
Tel: (949) 465-0900

Certificate Number: 2207130051

Single Channel Item

CALIBRATION DATA

Test Temp: 73 °F (23 °C) | Relative Humidity: 32 % | Excitation: 9.99 Vdc

Input Resistance: 355 Ω | Output Resistance: 355 Ω | Zero Balance: 0.0043 mV/V

Tension

Load (lb)	Output (mV/V)	Non-Lin. Error (% R.O.)
0	0.0003	0.000
440	0.2914	-0.108
800	0.5314	-0.059
1,200	0.7970	-0.084
1,600	1.0631	-0.072
2,000	1.3300	0.000
0	0.0008	0.000

Compression

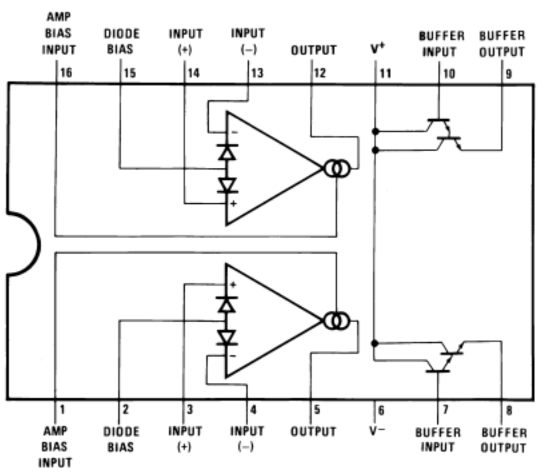
Load (lb)	Output (mV/V)	Non-Lin. Error (% R.O.)
0	0.0003	0.000
440	-0.2950	0.090
800	-0.5355	0.081
1,200	-0.8031	0.099
1,600	-1.0700	0.064
2,000	-1.3365	0.000
0	0.0000	0.000

APPENDIX G

LM13700 DUAL OPERATIONAL TRANSCONDUCTANCE AMPLIFIER INFORMATION

(Information from REFERENCE 13; LM13700 Datasheet)

Connection Diagram



3 Description

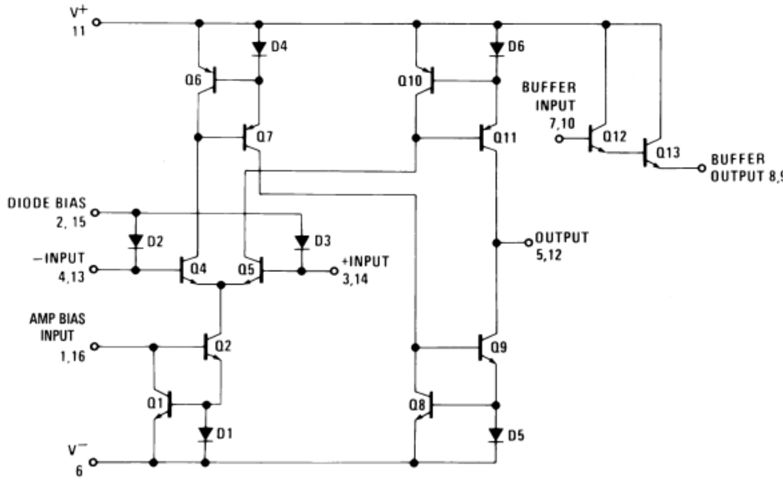
The LM13700 series consists of two current-controlled transconductance amplifiers, each with differential inputs and a push-pull output. The two amplifiers share common supplies but otherwise operate independently. Linearizing diodes are provided at the inputs to reduce distortion and allow higher input levels. The result is a 10-dB signal-to-noise improvement referenced to 0.5 percent THD. High impedance buffers are provided which are especially designed to complement the dynamic range of the amplifiers. The output buffers of the LM13700 differ from those of the LM13600 in that their input bias currents (and thus their output DC levels) are independent of I_{ABC}. This may result in performance superior to that of the LM13600 in audio applications.

Device Information(1)

PART NUMBER	PACKAGE	BODY SIZE (NOM)
LM13700	SOIC (16)	3.91 mm × 9.90 mm
	PDIP (16)	6.35 mm × 19.304 mm

(1) For all available packages, see the orderable addendum at the end of the data sheet.

7.2 Functional Block Diagram



7.3.1 Circuit Description

The differential transistor pair Q_4 and Q_5 form a transconductance stage in that the ratio of their collector currents is defined by the differential input voltage according to the transfer function:

$$V_{IN} = \frac{kT}{q} \ln \frac{I_5}{I_4} \tag{1}$$

where V_{IN} is the differential input voltage, kT/q is approximately 26 mV at 25°C and I_5 and I_4 are the collector currents of transistors Q_5 and Q_4 respectively. With the exception of Q_{12} and Q_{13}, all transistors and diodes are identical in size. Transistors Q_1 and Q_2 with Diode D_1 form a current mirror which forces the sum of currents I_4 and I_5 to equal I_{ABC}:

$$I_4 + I_5 = I_{ABC} \tag{2}$$

where I_{ABC} is the amplifier bias current applied to the gain pin.

For small differential input voltages the ratio of I_4 and I_5 approaches unity and the Taylor series of the ln function is approximated as:

$$\frac{kT}{q} \ln \frac{I_5}{I_4} \approx \frac{kT}{q} \frac{I_5 - I_4}{I_4}$$

$$I_4 \approx I_5 \approx \frac{I_{ABC}}{2} \tag{3}$$

$$V_{IN} \left[\frac{I_{ABC} q}{2kT}\right] = I_5 - I_4 \tag{4}$$

APPENDIX H

LCM325 LOAD CELL INFORMATION

(Information from REFERENCE 14; LCM325 Spec Sheet)

FEATURES

- Miniature size
- Fast response and low deflection
- Robust cable strain relief
- For use in both tension and compression

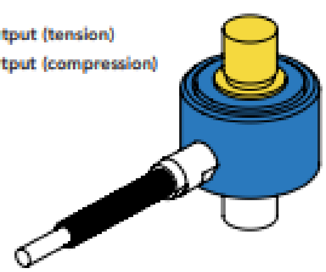
Non-loading surface, do not contact

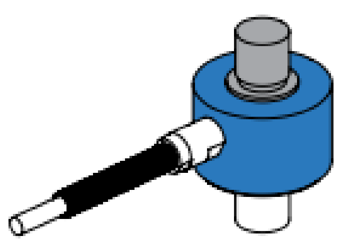
Active End

Fixed End

+ Output (tension)

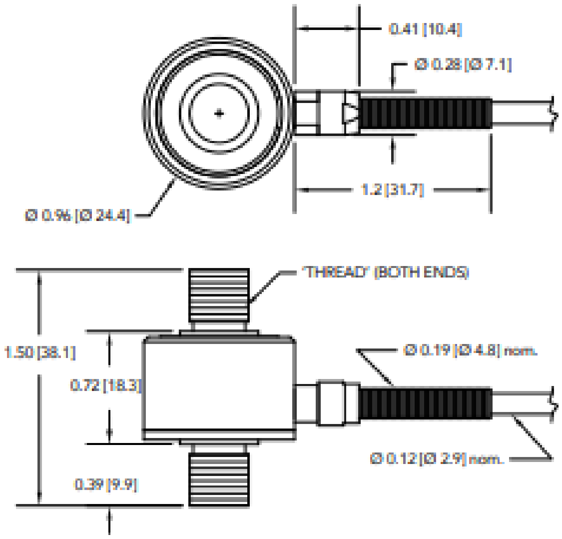
– Output (compression)





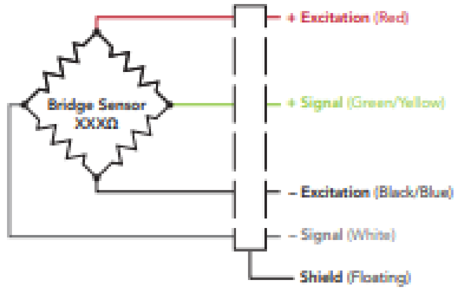
SPECIFICATIONS	
PERFORMANCE	
Nonlinearity	±0.5% of RO
Hysteresis	±0.5% of RO
Nonrepeatability	±0.1% of RO
ELECTRICAL	
Rated Output (RO)	1.3 mV/V (2 klb) 2 mV/V (3 klb)
Excitation (VDC or VAC)	18 max
Bridge Resistance	350 Ohm nom
Insulation Resistance	≥500 MOhm @ 50 VDC
Connection	#28 AWG, 4 conductor, braided shielded PVC cable, 10 ft [3 m] long
Wiring/Connector Code	WC1
MECHANICAL	
Weight (approximate)	4 oz [113 g]
Weight (minus cable)	1.8 oz [51 g]
Safe Overload	150% of RO
Deflection	0.001 in [0.05 mm] nom
Material (flexure)	17-4 PH stainless-steel
IP Rating	IP64
TEMPERATURE	
Operating Temperature	-45 to 200°F (-42 to 93°C)
Compensated Temperature	60 to 160°F (15 to 72°C)
Temperature Shift Zero	±0.005% of RO/°F (0.01% of RO/°C)
Temperature Shift Span	±0.02% of Load/°F (0.036% of Load/°C)
CALIBRATION	
Calibration Test Excitation	10 VDC
Calibration (standard)	5-pt Tension
Calibration (available)	Compression
Shunt Calibration Value	100 kOhm (2 klb), 60.4 kOhm (3 klb)
Conformity	
RoHS	EU 2015/863
CE	EN55011:2009; EN61326-1:2006

DIMENSIONS inches [mm]



WIRING CODE (WC1 WITH SHIELD)

RED	+ EXCITATION
BLACK	– EXCITATION
GREEN	+ SIGNAL
WHITE	– SIGNAL
SHIELD	FLOATING



CAPACITIES

ITEM #	klb	kN	Thread	Natural Frequency (kHz)
FSH04009	2	8.9	3/8-24	18
FSH04008	2	8.9	M10x1.5	18
FSH04006	3	13.3	3/8-24	18
FSH04007	3	13.3	M10x1.5	18

APPENDIX I

SPI 12-3 STRING POTENTIOMETER INFORMATION

(Information from REFERENCE 15; SPI 12-3 Spec Sheet)

SP1

Compact String Pot • Voltage Divider

Linear Position to 50 inches (1270 mm)

Rugged Polycarbonate Enclosure • IP67 Optional

Mounting Bracket & Optional Sensor Cover w/Connector

IN STOCK for Quick Delivery!

This compact stringpot with "voltage divider" output, provides ease-of-use and flexibility for measurement ranges up to 50 inches. Made of rugged polycarbonate, the SP1 fits in small spaces, doesn't need perfect alignment and ships with a stainless steel mounting bracket to let the user easily orient this sensor in just about any direction imaginable.

The SP1 is available with a connector, mating plug and sensor cover to protect against IP67 (wet) environments and a lower cost, "open" sensor version priced for both the budget conscious single piece user and the OEM alike.

Ordering Information

includes sensor & mounting bracket

Part Number	full stroke range	accuracy	max. acceleration	measuring cable tension (± 25%)	cycle life
SP1-4	4.75 in (120 mm)	1.00%	15 g	7oz. (1,9 N)	2.5M
SP1-12	12.5 in (317 mm)	.25%	15 g	7oz. (1,9 N)	500K
SP1-25	25 in (635 mm)	.25%	15 g	7oz. (1,9 N)	500K
SP1-50	50 in (1270 mm)	.25%	15 g	7oz. (1,9 N)	250K

includes sensor, mounting bracket & mating connector

Part Number	full stroke range	accuracy	max. acceleration	measuring cable tension (± 25%)	cycle life
SP1-4-3	4.75 in (120 mm)	1.00%	11 g	11.5 oz. (3,2 N)	2.5M
SP1-12-3	12.5 in (317 mm)	.25%	11 g	13.9 oz. (3,7 N)	500K
SP1-25-3	25 in (635 mm)	.25%	11 g	11.5 oz. (3,2 N)	500K
SP1-50-3	50 in (1270 mm)	.25%	11 g	11.5 oz. (3,2 N)	250K

Optional Cordset

Part No.

9036810-0040 for all SP1-xx-3 versions, an optional 13-ft. cordset with 4-pin M12 connector

Complete Specifications

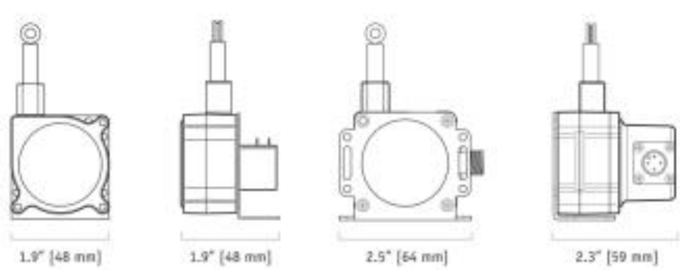
Available Stroke Ranges	0-4.75, 0-12.5, 0-25, 0-50 inches
Output Signal	voltage divider (potentiometer)
Accuracy	±0.25 to ±1.00% (see ordering info)
Repeatability	± 0.05% full stroke
Resolution	essentially infinite
Measuring Cable	0.019-in. dia. nylon-coated stainless steel
Measuring Cable Tension	see ordering information
Maximum Cable Acceleration	see ordering information
Enclosure Material	Polycarbonate
Sensor	plastic-hybrid precision potentiometer
Weight, max. (includes bracket)	.4 lbs (.19 kg)

Electrical

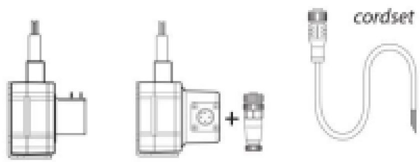
Input Resistance	10K ohms, ±10%
Power Rating, Watts	2.0 at 70°F derated to 0 at 250°
Recommended Maximum Input Voltage	30 V (AC/DC)
Output Signal Change Over Full Stroke Range	94% ±4% of input voltage
Electrical Connection, SP1-xx	solder terminals
Electrical Connection, SP1-xx-3	4-pin, M12 connector

Environmental

Enclosure	IP 50 (SP1-xx), IP67 (SP1-xx-3)
Operating Temperature, SP1-xx	0° to 160°F (-18° to 70°C)
Operating Temperature, SP1-xx-3	-40° to 160°F (-40° to 70°C)
Vibration	up to 10 g to 2000 Hz maximum

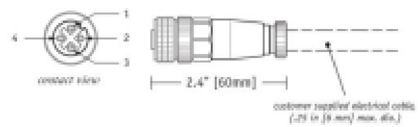


Electrical Connection

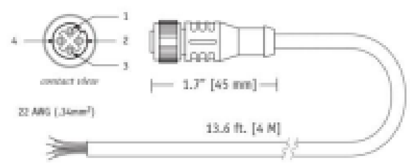


Signals	solder terminals	pin	pin - colorcode
+in	#3 (cw)	1	1 - brown
common	#1 (ccw)	2	2 - white
+out	#2 (s)	3	3 - blue
n/c		4	4 - black

field installable connector (included)

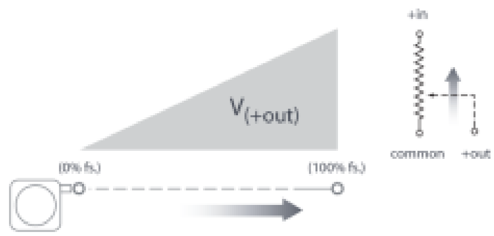


cordset, part no. 9036810-0040 (optional)

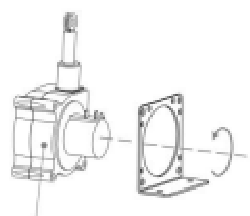


Terminal/Pin Location (SP1-xx)

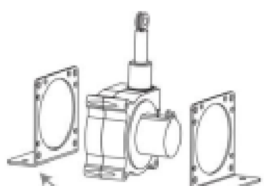
Output Signal



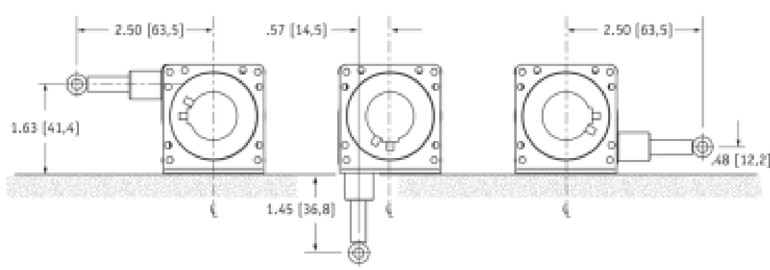
Mounting Options for SP1-xx:



To change measuring cable direction simply remove the 3 bracket attaching screws and rotate sensor body to desired direction.



For added flexibility, mounting bracket can easily be switched to the opposite side.



APPENDIX J

ANALYSIS OF SENIOR PROJECT DESIGN

Project Title: Instrumented Control Column for an Optionally Piloted Aircraft

Student's Name: Andrew Klein **Student's Signature:**

Advisor's Name: Benjamin Hawkins **Advisor's Initials:** BH **Date:** 6/12/2023

• **Summary of Functional Requirements**

Describe the overall capabilities or functions of your project or design. Describe what your project does. (Do not describe how you designed it).

This project provides Natilus with a prototype of a two-part sensor system for their control column. One functional aspect is the position sensing system, which is modular and can be mounted to the control column linkages once the Natilus completes their Iron Bird. The other element is the force sensing system. This project provides an initial design and test data for the simultaneous operation of multiple load cells. This system is not yet fully functional. Thus, solutions to this issue and the recommended next steps are provided as part of the project deliverables.

• **Primary Constraints**

Describe significant challenges or difficulties associated with your project or implementation. For example, what were limiting factors, or other issues that impacted your approach? What made your project difficult? What parameters or specifications limited your options or directed your approach?

A significant challenge was working in tandem with the Natilus team remotely. As the design changed and developed further, many of the requirements and priorities would shift. The Iron Bird, which was originally slated to be under construction before the project was completed, was put on the back-burner for a while as Natilus began to work on a scaled RC model aircraft. This was something that shrank the scope of the project and placed the priority on the position sensing system as that would help bring in more money for the company.

Other than this, the project definition was broad and a lot of it was left open-ended. This was a challenge and a good learning experience, as I grew as an engineer and project manager. The engineers at Natilus were always available and were a major source of help/info, but all the critical design choices were left to me.

• **Economic**

- *What economic impacts result? Consider:*
  - *Human Capital – What people do.*
  - *Financial Capital – Monetary instruments.*
  - *Manufactured or Real Capital – Made by people and their tools.*
  - *Natural Capital – The Earth's resources and bio-capacity.*

The main economic impacts of this project are tied into Natilus's purpose as a whole; to revolutionize the "status quo of freight transportation through innovation and advanced technologies to make air freight costs competitive to cargo shipping and dramatically improve delivery times."

This project was conducted to aid Natilus in that mission to become an industry competitor and redefine the standard for faster, cheaper, and more sustainable shipping. Aerospace is an industry with a lot of financial capital behind it, and the unique approach Natilus is taking makes it incredibly attractive to investors. However, nothing speaks quite like progress and results. The successful completion of this project surely aided in bringing Natilus one step closer to those results.

The ZeroAvia partnership to use hydrogen-electric propulsion engines also makes Natilus a competitive sustainable shipping option for the future. This demonstrates the company's respect for the Earth's natural capital and their efforts to make great strides towards reducing emissions in the freight industry.

- *When and where do costs and benefits accrue throughout the project's lifecycle?*

- *What inputs does the experiment require? How much does the project cost? Who pays?*
  Original estimated cost of component parts (as of the start of your project).
  Actual final cost of component parts (at the end of your project)
  Attach a final bill of materials for all components.
  Additional equipment costs (any equipment needed for development?)
- *How much does the project earn? Who profits?*

Costs for Natilus accrue mainly when person-hours stack up. By taking a detailed but efficient approach to the design process this was mitigated as much as possible. The initial large purchase of the sensors was also a large purchase, but these sensors will be usable all the way up to the first flight aircraft which makes them a time and money saving investment. As this is a Natilus project, all costs fall on them.

This project on its own earns no money for Natilus. But they deem it worthwhile because it is a part of a necessary test process to demonstrate the HIL functionality of their design. It is this future testing phase that has the potential to bring in millions of dollars in pre-purchase agreements and investment revenue.

For the original cost estimate see Table 5 under "Cost Estimate". There were no additional material costs however the labor costs did exceed the expected amount. The estimation was 3 hours every week for 28 weeks, but this ended up averaging to closer to 5 hours. The updated labor cost then become $3780, which is $1512 greater than anticipated.

- *Timing*
  When do products emerge? How long do products exist? What maintenance or operation costs exist?
  Original estimated development time (as of the start of your project), as Gantt or Pert chart
  Actual development time (at the end of your project), as Gantt or Pert chart
  What happens after the project ends?

The project was scheduled well and remained on track for the whole duration. The only notable change was an update to the senior project expo which happened a week earlier than expected. This did not affect the project result, as the signup window was missed, and no participation was required. The testing phase yielded some important data and helped identify some improvements to be made next. Outside of the scope of this project, I will continue to work for Natilus in a full-time position. This will allow me to make these necessary changes myself as the next iterations of the project advance towards implementation in the Iron Bird.

• If manufactured on a commercial basis:
• Estimated number of devices sold per year
• Estimated manufacturing cost for each device
• Estimated purchase price for each device
• Estimated profit per year
• Estimated cost for user to operate device, per unit time (specify time interval)

Not applicable to this project

• Environmental
• Describe any environmental impacts associated with manufacturing or use, explain where they occur and quantify.
• Which natural resources and ecosystem services does the project use directly and indirectly?
• Which natural resources and ecosystem services does the project improve or harm?
• How does the project impact other species?

For an analysis of the project's environmental considerations see "Impact Analysis"

• Manufacturability
• Describe any issues or challenges associated with manufacturing.

This will be more of a challenge during the next iteration of the project when moving to PCBs. There were some significant troubles with connecting breadboards and wires that introduced noise to the system. In this case, a lack of custom manufacturing processes led to issues.

• Sustainability
• Describe any issues or challenges associated with maintaining the completed device, or system.
• Describe how the project impacts the sustainable use of resources.
• Describe any upgrades that would improve the design of the project.
• Describe any issues or challenges associated with upgrading the design.

• Ethical
• Describe ethical implications relating to the design, manufacture, use, or misuse of the project.

For an analysis of the project's ethical implications and stance on sustainability see "Impact Analysis"

• Health and Safety
• Describe any health and safety concerns associated with design, manufacture or use of the project.

For a detailed analysis of the potential health and safety concerns see Appendix A; FMEA.

• Social and Political

• Describe social and political issues associated with design, manufacture, and use.
• Who does the project impact? Who are the direct and indirect stakeholders?
• How does the project benefit or harm various stakeholders?
• To what extent do stakeholders benefit equally? Pay equally? Does the project create any inequities?
• Consider various stakeholders' locations, communities, access to resources, economic power, knowledge, skills, and political power.

For an analysis of the project's social and political Implications see "Ethics" and Table 6 under "Impact Analysis".

• Development

• Describe any new tools or techniques, used for either development or analysis that you learned independently during the course of your project. Include a literature search.

Learning to work with both sensor types was a new experience. Load cells and String POTs are expensive, so I had never had the chance to work with either before. Tt was extremely rewarding using the skills developed at Cal Poly to interpret product manuals and datasheets to design these circuits. Additionally, working on this in-depth with MATLAB Simulink within the Natilus Sim has been a major learning experience. There is a lot to learn within the specific toolboxes used and the custom blocks used throughout the large simulator. Much of this work could not be shown for proprietary reasons, but I grew the most as an engineer by exploring the software aspect of this project.

For information on the project view "Background" and for the resources consulted and used to gather this information see "References".

The datasheets were used to confirm that components were within the engineering requirements and to inform the designs of the circuits and systems. Max ratings and pin diagrams were especially important for this. The communications with Nautilus and their engineering team were the biggest resource. This communication happened weekly and allowed for the exchange of ideas and progress reports. Additional resources such as the noise reduction technique document for the IA100 amplifier were included to be useful in the future as the noise issue gets tackled in the load cell system. The literature on flight control systems was beneficial as it allowed me to gain a basic understanding of some aircraft systems. This informed the design and gave me confidence when making decisions or interpreting data.