

Robotic Flight Simulator

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by

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Robotic Flight Simulator

ABSTRACT.....	5
INTRODUCTION.....	6
Problem.....	6
Credibility.....	7
Project Goals.....	8
Acknowledgements.....	8
DISCUSSION.....	9
Project Concept.....	9
Design Objective.....	10
Vision.....	11
Robotics.....	12
End Effector.....	16
Main Control Panel.....	18
PLC.....	20
HMI.....	21
Communication.....	22
Manufacturing.....	23
Safety.....	32
Budget.....	33
Timeline.....	37
Lessons Learned.....	38
Future Recommendations.....	40
CONCLUSION.....	41
Benefactors.....	41
Conclusion.....	41
References.....	41



APPENDIX	42
Appendix A: HMI Program	42
Appendix B: PLC Program	42
Appendix C: Vision Program	42
Appendix D: Computer <—> PLC Communication Program	42
Appendix E: Robot Main Program	42
Appendix F: Robot Background Program.....	42
Appendix G: 3D Print STL Files	42
Appendix H: Datasheets.....	42
Appendix I: EH&S Robotic Safety Procedure	43
Appendix J: Rhodes 401 Robotic Safety Procedure	51
Appendix K: CAD Diagrams and Layouts.....	52

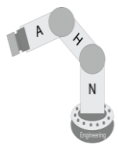
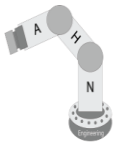
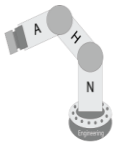


Figure 1: Boeing 737 Flight Simulator ^[1]	6
Figure 2: Concept Map.....	9
Figure 3: System Layout	10
Figure 4: Head Pose Estimation Annotation ^[2]	11
Figure 5: Robot Path	12
Figure 6: Angle Limits.....	13
Figure 7: Radius vs Angle	13
Figure 8: Main Robot Program.....	14
Figure 9: Background Robot Program.....	15
Figure 10A: Control Panel Layout	17
Figure 10B: Control Panel Layout	17
Figure 11A: Main Control Panel Layout	18
Figure 11B: Main Control Panel Layout	19
Figure 12: Allen Bradley PLC	20
Figure 13: Play HMI Screen	21
Figure 14: Settings HMI Screen.....	21
Figure 15: IP Address	22
Figure 16: Terminal Output.....	22
Figure 17: Camera Mounts	23
Figure 18: Foam Mounts.....	24
Figure 19: Circuit Breaker Cover	25
Figure 20: Sola Power Supply Cover	26
Figure 21: Ethernet Switch Mount.....	27
Figure 22: Power and Output PCB Schematic.....	28
Figure 23: Power and Output PCB Layout	29
Figure 24: Input PCB Schematic	30
Figure 25: Input PCB Layout.....	30
Figure 26: Post CNC Milling.....	31
Figure 27: Roboguide Simulator	32
Figure 28: Bill of Material (1/3).....	33
Figure 29: Bill of Material (2/3).....	34
Figure 30: Bill of Material (3/3).....	35
Figure 31: Hourly Breakdown	36
Figure 32: Timeline	37
Figure 33: Fanuc Robot	38
Figure 34: Fanuc Installation Base	39



ABSTRACT

The system is a Robotic Flight Simulator. The system further develops human-robot interactions by utilizing vision processing and a collaborative robotic arm to interact with the user. This is one more step towards having robots respond to gestures, facial expressions, and human motion in real time. The vision system utilizes OpenCV written in python to handle the vision processing and communicates to a Kuka iiwa robot that manipulates the end effector around a person within arc. The end effector is a small control panel outfitted to look like a mini mockup of a control panel for user interaction. This is a static / dynamic robot system where the robot has a specified route it will follow but it is based on human feedback through vision. In the future, using this progress, we will be able to further improve upon more dynamic robot systems that react with human feedback. Most robotic arm solutions involve static paths that do not change based off of human input. With the rise in collaborative tasks between humans and robots within the industry, it is imperative that the technology be developed to further develop these interactions. A possibility with this research is to create a robotic system that is able to care for the elderly or sick with simple tasks, such as lifting a table or reaching for items on the floor.



INTRODUCTION

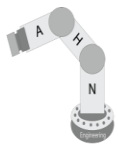
The project completed is a Robotic Flight Simulator. The purpose of the robotic flight simulator is to reduce the cost of flight simulators and to increase the research into human-robot interaction. This document covers the following: Problem, Solution, Implementation, and Benefactors of designing and building a robotic flight simulator. The project will encompass the material the team has learned within the classroom and while on Co-Op. This project allows the team to demonstrate electrical hardware design, programming, robotics, and project management.

Problem

The cost to construct a standard full-scale flight simulator is extremely high in comparison to the cost of a robotic system. An example of a flight simulator is shown in Figure 1 below. With the greatest cost of the project being the robot and a typical robotic arm being ~\$65,000, there is large cost savings when compared to a typical simulator. The remaining components at commercial cost would be approximately \$10,000. Also, as more robots are increasingly integrated into the workforce, more research needs to be completed on how humans and robots can interact. The outcome of how the robot will react to human interaction, as well as how a human will interact with a robot. These interactions can be monitored by force sensors, cameras, switches, pressure mats, etc.



Figure 1: Boeing 737 Flight Simulator ^[1]



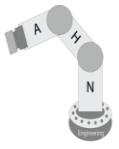
Credibility

The three students, Austin Kucinski, Heath Palmer, and Nathan Huber are all pursuing a Bachelor of Science in Electrical Engineering Technology at the University of Cincinnati. Each student has experience with electrical design and programming within industrial and research environments. Individually, each student has greater strengths within a section of the electrical field. Austin specializes in industrial hardware design and integration, Heath specializes in vision and camera utilization, and Nathan specializes in industrial programming, vision, and robotics. The concept map in Figure 2 shows how the experiences the group gained within the classroom and on Co-Op interlink with the proposed project. All of these skills, classroom and hands-on, will further strengthen the quality and durability of the project proposed.

Austin has gained experience throughout school and co-op including electronics design, programming, and integration. In addition, his control systems work at Cincinnati Test Systems and Automation Plus/Process Plus designing control panels for process plants and integrating automated test fixtures further adds to fact that the function and operation of the EOAT/Control Panel is easily achievable. In addition, his software development and programming skills will be a helpful asset. The application of each of these skills and other general skills will result in a finished product based on the original design.

Heath gathered theory and hands-on experience with Virtual and Augmented Reality development, through co-op, personal projects, and undergraduate research. This includes the use of tracked user data in an application. Heath attended the 2018 Reality Virtually USC Hackathon where his team created a mobile app to track three points on a human arm, then overlay the appearance of muscle or skeleton layers for educational purposes. This application used the mobile camera for tracking and Unity 3D for application development. Although different development software, Heath has shown adaptability and promise to complete this product.

Nathan has a strong background in robotics, vision, and industrial control systems. This experience has been gained from working at Coldwater Machine, personal projects, and undergraduate research. Nathan is skilled in four different robotic programming languages and proficient in over ten programming languages. Also, Nathan is certified in Fanuc Collaborative Robotics and Dual Check Safety. With these skills, Nathan managed the software, vision, and robotics of a 22 robotic industrial system in a fraction of the quoted time for an automotive supplier. Using the experience and skills preserved, Nathan has the capability to accomplish the task at hand.



Project Goals

There are several goals that have been identified. The main goal is to improve the research within human – robot collaboration. The collaborative robotic market is rapidly growing and there is minimal research on how humans can better interact with robots. Part of the research being done within this project is how this collaboration can improve training of systems within aerospace. The robotic arm will manipulate its end effector around a person within an arcing fashion to simulate the rounded shape of a cockpit. The project is not a final solution but a stepping stone to further research.

The use of robotics is rapidly growing within today's world. As the need for humans and robots to interact increases, the development of the collaborative robot market has increased. Both the Kuka or the Fanuc robot used for this project is a collaborative robot. Both robots meet the ISO standard to allow direct human interaction safely. Collaborative robots (Cobots) have only been used within the market for a short period of time now. By further developing software and motion controls to interact with different methods, the relationship can be improved.

The cost of flight simulators can be up over 12 million dollars depending on the size and features required. ^[4] As this project further develops past the goals stated, it is anticipated to use virtual reality technology to provide a more proper visual feedback while providing the kinesthetic feedback of the control panel being manipulated around the person with a robot. Although the VR technology will not be included within this scope of work, it is designed to allow future members of the engineering community pick up with what is completed.

Acknowledgements

We would like to the following people / businesses for their support or donations to our project.

- Dr. Ma, for allowing us to utilize his facilities and provide guidance on the end goal of the project.
- Professor Rabiee, for his guidance and support of our project.
- Jason Heyl, for 3D printing parts and allowing us to use his cart to transport the robot to and from Tech Expos.
- David Tashjian, for supplying a desktop to use for Logix5000 and vision processing.
- Fanuc America, for heavily discounting a Fanuc CR35iA robot.
- CBT & HMS, for heavily discounting an Anybus EtherCAT to Ethernet/IP converter.
- Coldwater Machine Company, for allowing Nathan to use a Roboguide license for robotic simulations.



Design Objective

The project will contain several components shown below in Figure 3. The system will utilize a variety of embedded systems, communication protocols, and power systems. The camera on the end of arm tooling (EOAT) will monitor the user's head angle and relay this information to a Raspberry Pi. The Raspberry Pi will relay the information from the EOAT to the main control panel over Ethernet/IP. Finally, the PLC handles the robot control and the HMI mounted on the end effector. The Arduino Nano located inside the EOAT Cabinet will control the switches and LEDs for human interaction. The Kuka iiwa is the robot used for demonstrating the system. Earlier in the proposal phase of the project, a Fanuc CR35iA robot was purchased for the intent of this project but due to installation delays, the Kuka iiwa is used as a substitution. This does not change the overall scope or goals for the project but what hardware was used to complete this task.

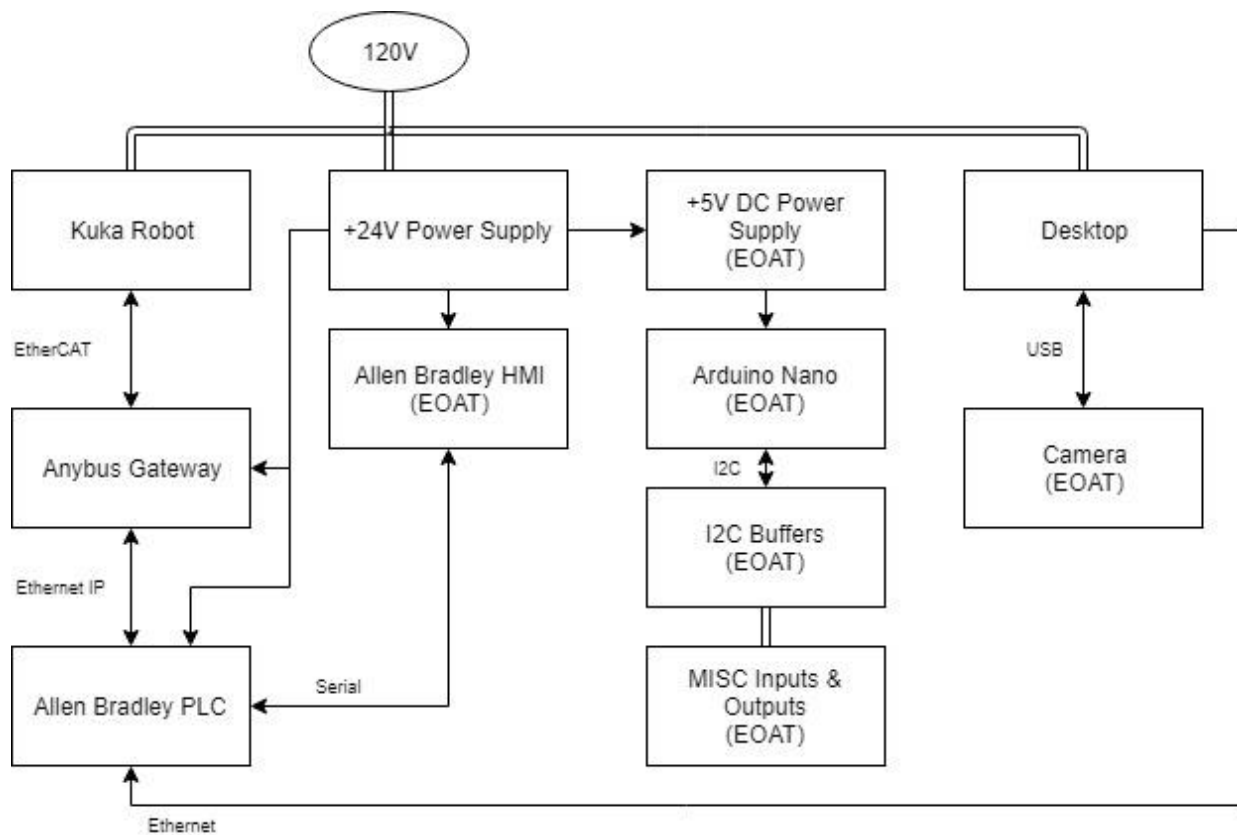
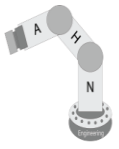


Figure 3: System Layout



Vision

The problems stated will be resolved by implementing a robotic arm that responds to the user's head position. The video to be processed is collected by a Logitech HD C920 Camera. A powerful desktop will parse the data using an open source software called OpenCV with a library called "Head Pose Estimation" by GitHub user Lincolnhard. [2] The Head Pose Estimation library will provide an estimated output of the yaw, pitch and roll of the user's face. The software identifies 68 points on the user's face shown in Figure 4 below.

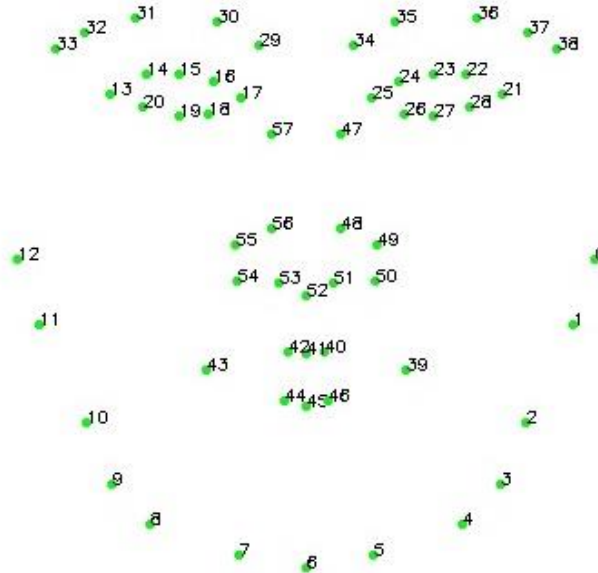


Figure 4: Head Pose Estimation Annotation [2]

The robot requires the Pitch value from the python script to be sent to the robot. The data is filtered by running a weighted average of the data collected and transmits the data to the PLC if it exceeds a certain threshold of the previous data transmitted to the PLC. The data transmitted to the PLC from the desktop uses the library ruscito/pycomm. [3]



Robotics

The data collected is the user's cartesian angular coordinates (Yaw, Pitch, and Roll) within the camera's field of view. The Pitch (P) data will be parsed and converted into a 16-bit integer value and transmitted to the PLC over Ethernet. The modified vision program will determine the threshold of when to tell the robot to move to the new coordinate values. This prevents the PLC from being spammed with data it already knows. The robot takes the new head angle provided by the PLC and computes its path to follow within an arc fashion. A slight variation of this is shown in Figure 5 below.

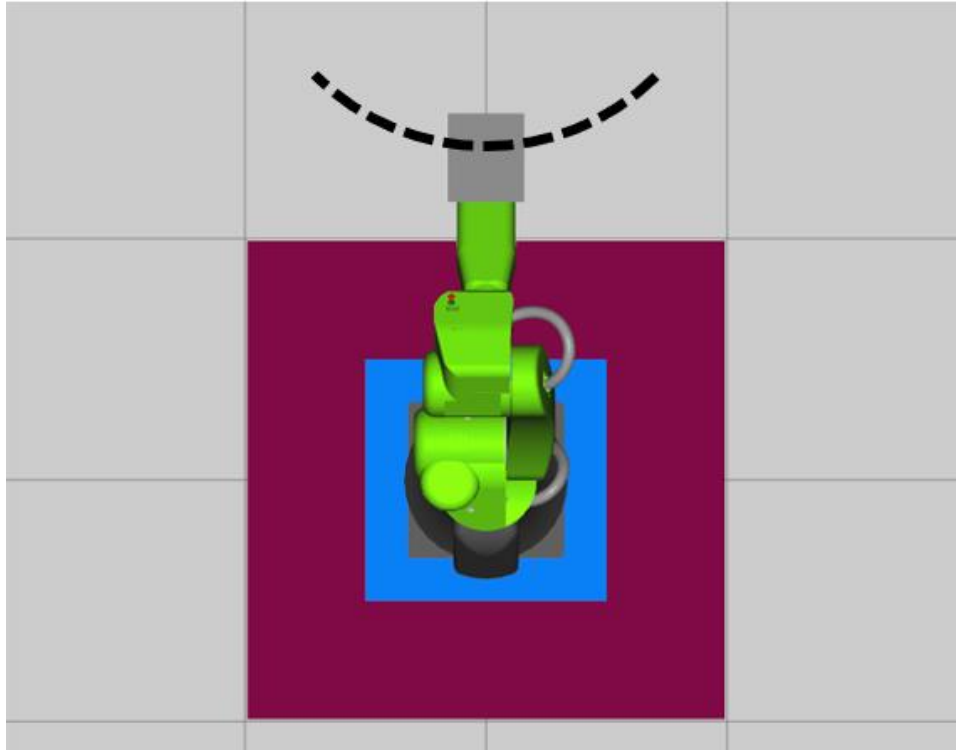
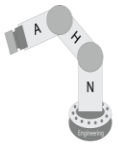


Figure 5: Robot Path

The radius of the arc can be set through the C600 HMI mounted within the control cabinet. This allows the user to have the flexibility when wanting to simulate different sized cockpits of airplanes. For example, a smaller airplane will have a smaller radius to the oblong shaped cockpit while a larger airplane will have a larger radius. A downside to the current layout is that the robot has a max reach and the larger the radius, the decreased angular capabilities it has. An example is the Kuka iiwa 14 robot, at a radius of 500mm the max angle the user's head can go is +- 40 degrees. At a radius of 600mm the max angle that the robot can reach is +- 28 degrees. This is assuming the robot's end effector is at a distance of 175mm from the base in the X coordinate plan with an overall angle of zero. The robot calculates the max angle that it can rotate about along the specified radius in the background. The equation to calculate this is shown below in Equation 1.

$$\text{Max Angle} = (\text{Radius} * 0.135 + 108.5) * \text{Safety Factor} \quad (1)$$



This equation was developed by removing the max angle limits internal to the robot program and allowing the robot to run until it faults stating that the position cannot be reached. This data was recorded and shown in the table below in Figure 6.

Radius	Height	Max Angle
400	400	57
	500	55
	600	55
500	400	41
	500	41
	600	40
600	400	29
	500	28
	600	28

Figure 6: Angle Limits

The data shown in Figure 6 above is plotted in Figure 7 below to show the data is relatively linear. There is a slight dip in the Max Head Angle around 500mm but in comparison to the linear dashed line, it is close enough for these purposes to consider linear. The “R” value also proves the visual assumptions due to the slight difference between the “R” value and one.

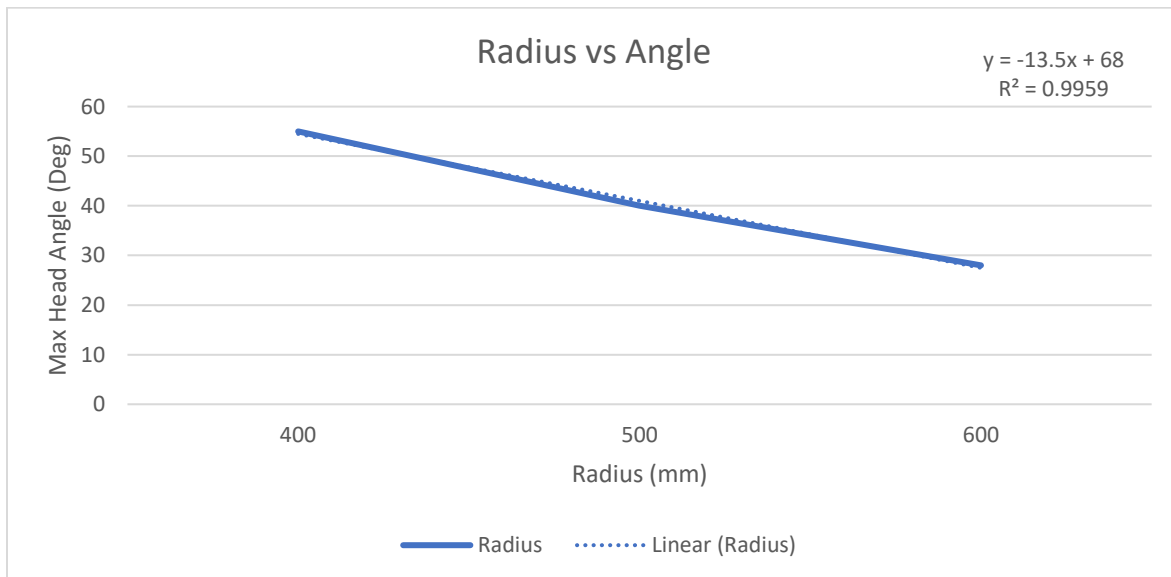
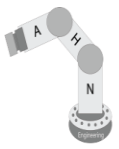


Figure 7: Radius vs Angle

A safety factor of 10 % is taken into account to prevent any accidental overreach. This equation is constantly executed in the background to ensure any changes in the radius are accounted for within the limits of the robots reach.



Also, the Z height that the control cabinet is manipulated upon is dynamically changed within the HMI shown in Figure 14. This allows different height users to interact with the simulator comfortably. This is also a solution to different height control systems.

An outline of the main robot program is shown below in Figure 8.

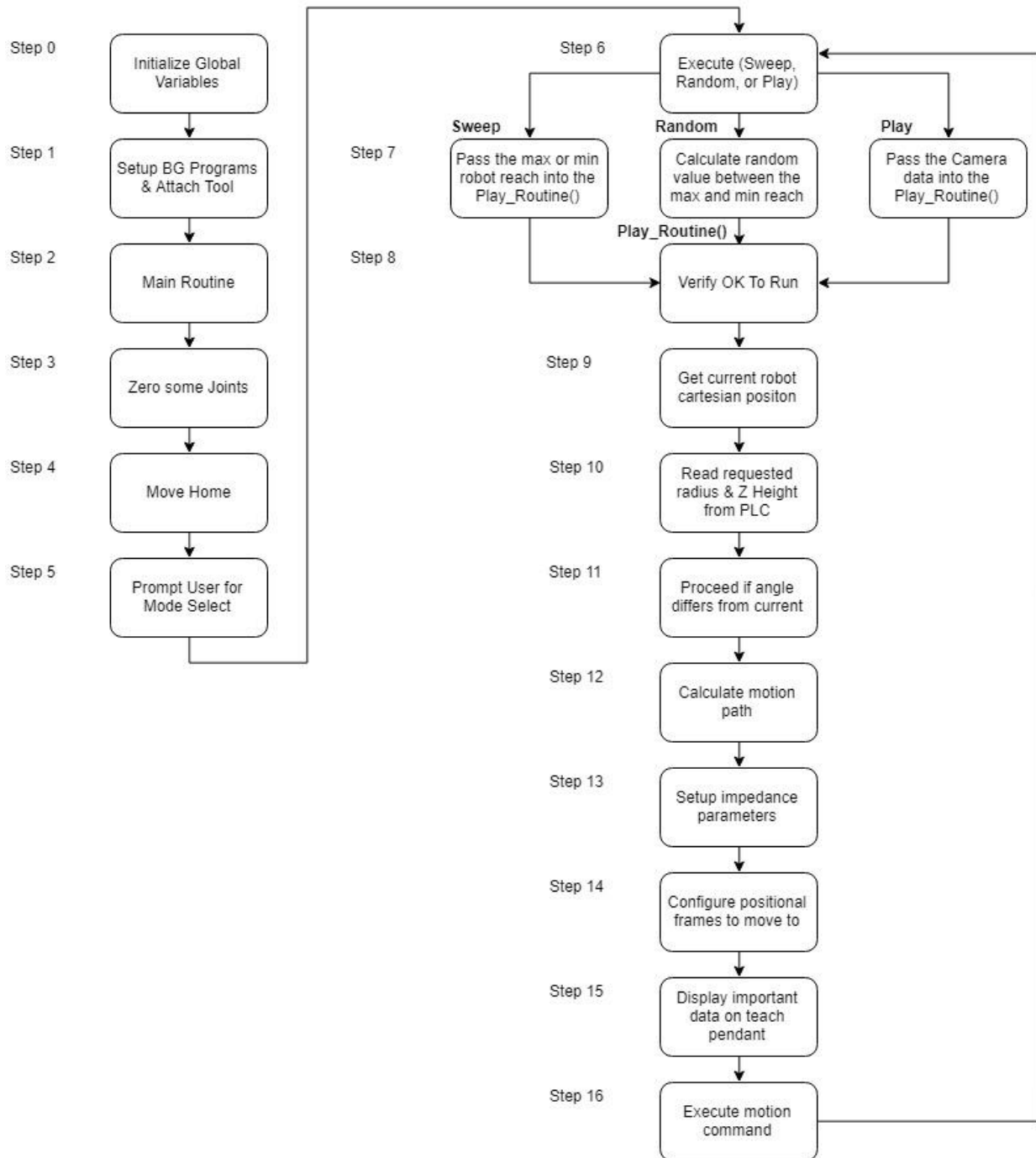
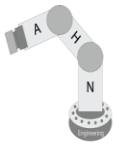


Figure 8: Main Robot Program



An outline of the background robot program is shown below in Figure 9.

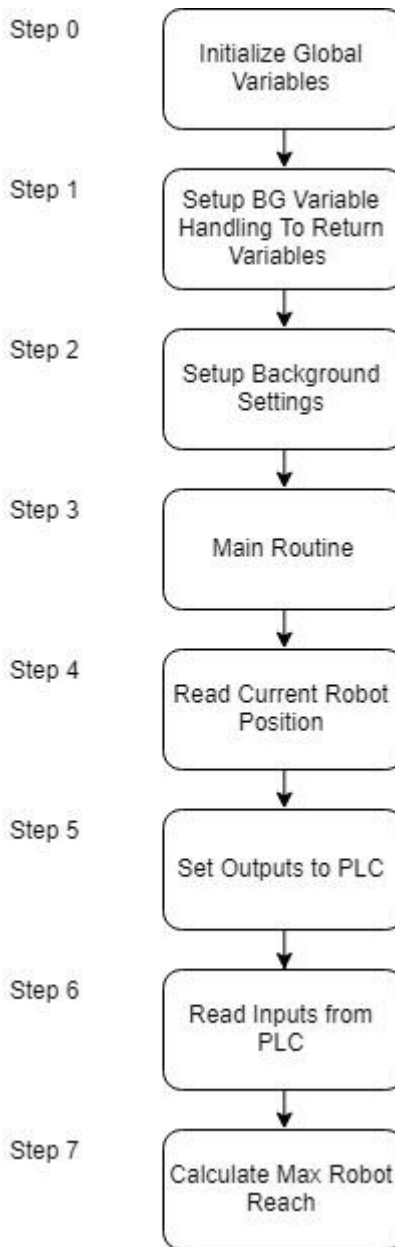
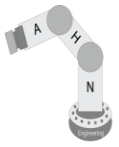


Figure 9: Background Robot Program



End Effector

The user interacts with the control panel mounted on the end effector of the robot. The control panel has two main purposes, Play Mode and Robot Configuration (Settings). The “Play Mode” is a screen that the user is able to interact with that has no correlation with the systems operation.

The design ideology for the control panel is to mimic an aircraft flight control panel in both loose aesthetic and mechanical function. Therefore, the research required for the design of this panel consisted of compiling several different, actual, aircraft flight control panels and drawing similarities. With the overall design scheme selected, buttons and switches were selected to provide different types of hand/finger mechanics when interacting with the panel; E.g. square momentary pushbutton, circular latching pushbutton, toggle switch, others.

The operation of the switches and indicators are controlled by an Arduino Nano. The Arduino Nano does not have sufficient I/O pins for the number of devices designed for. Therefore, an I²C buffer is implemented with a 16-Bit I²C I/O Expander to expand the number of I/O pins and to account for any problems with bus capacitance. These integrate with the manufactured PCBs to supply all the inputs and outputs communicated to the Arduino. A 4-digit 7-segment display with an I²C backpack is also integrated into the user feedback setup. A stop button is mounted on the front of the control panel and integrated into the PLC I/O to request the robot to stop. The completed panel and panel layout are shown in Figure 10A and Figure 10B below.

There are two programs developed for the control panel. The first is a simple “test” program designed for simple input and user feedback. For example, when a button is pressed, an LED is activated; when a selector switched is turned, a different display is called for the 7-segment display. The second program developed includes this test program, but adds another element called “Game mode”. In this mode, the selector switch is used to start, and an indicator is randomly chosen and lit. The user then required to activate the corresponding input. If correct, the program gives the user the “correct feedback”, if incorrect, the program notifies the user and the same button is re-lit.



Figure 10A: Control Panel Layout

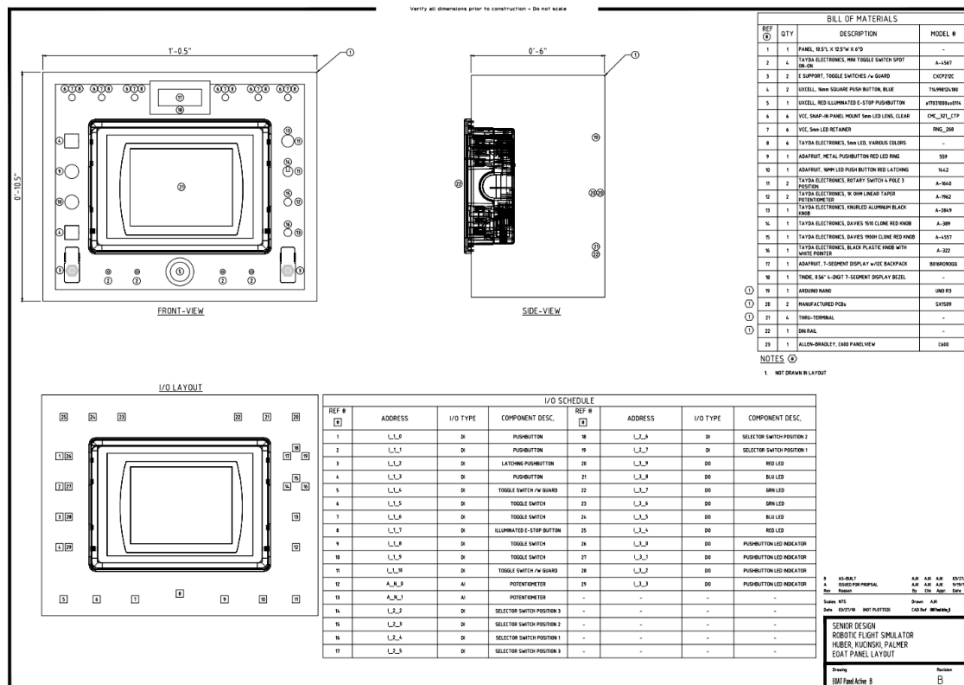
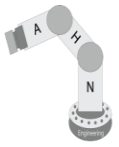


Figure 10B: Control Panel Layout



Main Control Panel

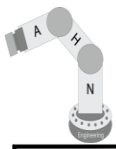
The Main Control Panel will contain the following:

- Power supplies
- Allen Bradley PLC
- Ethernet Switch

The Allen Bradley PLC will communicate any information over Ethernet/IP to an Anybus EtherCAT to Ethernet/IP converter to communicate to the robot. The PLC will send and receive information from the C600 HMI over serial and the computer will communicate over Ethernet to the PLC. The incoming 120VAC will be switchable fused to allow the power of the whole system to be turned off from the control panel, as well as a fuse for the power supply. The backplane is made from painted plywood and 1" conduit was used as wireway. The completed main control panel and panel layout is shown in Figure 11A and Figure 11B below.



Figure 11A: Main Control Panel Layout



Robotic Flight Simulator

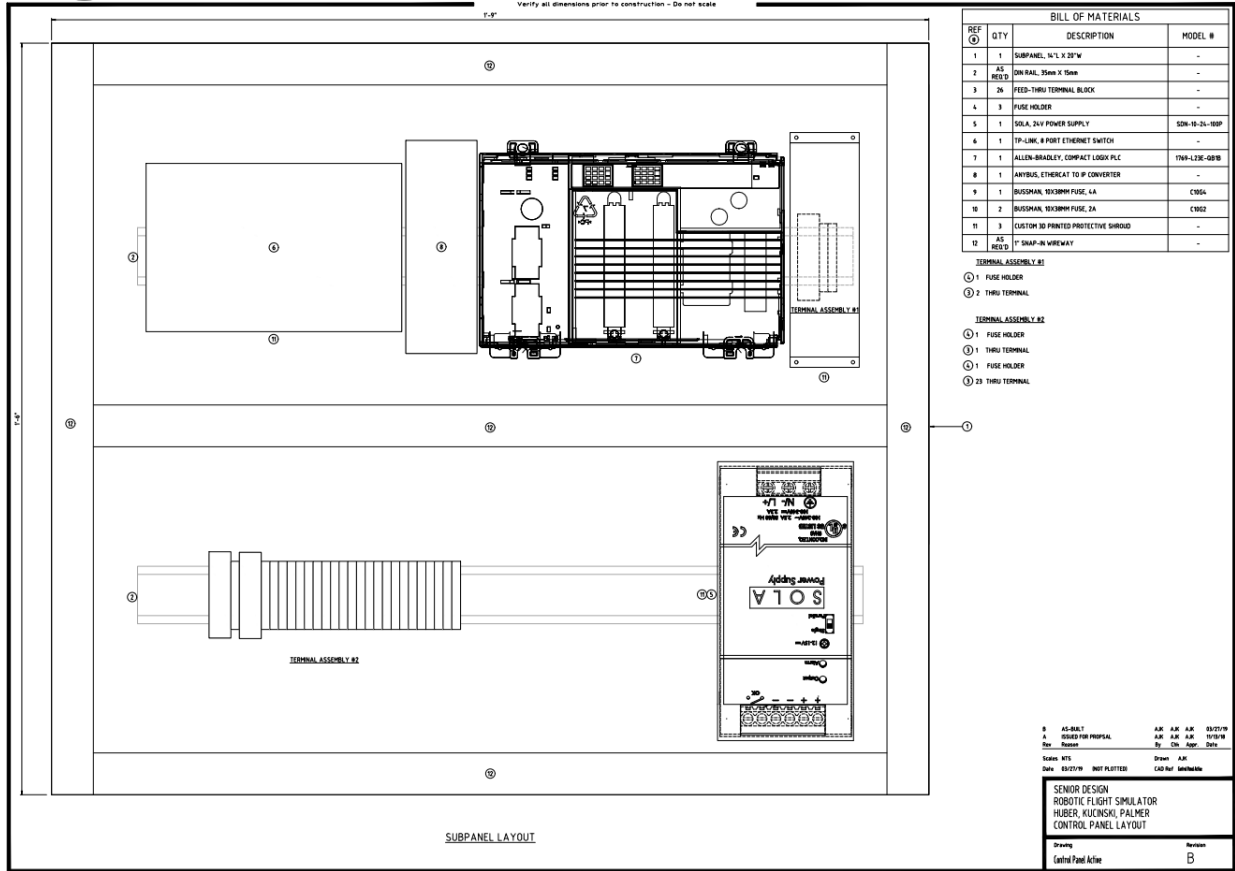
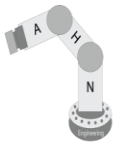


Figure 11B: Main Control Panel Layout

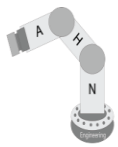


PLC

The CompactLogix PLC is used as a pass through between the Computer Vision system and the robot. Some of the data such as the robot's Cartesian position and head angle are shown on the HMI. The PLC also has miscellaneous timers and bits that interact with the HMI's "Play" screen interface. The data to be sent to the robot from the Vision Computer system is written to the PLC by using a python library called Pycomm by Ruscito. ^[3] The PLC is shown in Figure 12 below.



Figure 12: Allen Bradley PLC



HMI

The C600 HMI allows the user to interact with a “Play” screen and “Settings” screen. The “Play” screen has various buttons, dials, and indicators that the user can be engaged with. See screen in Figure 13 below.

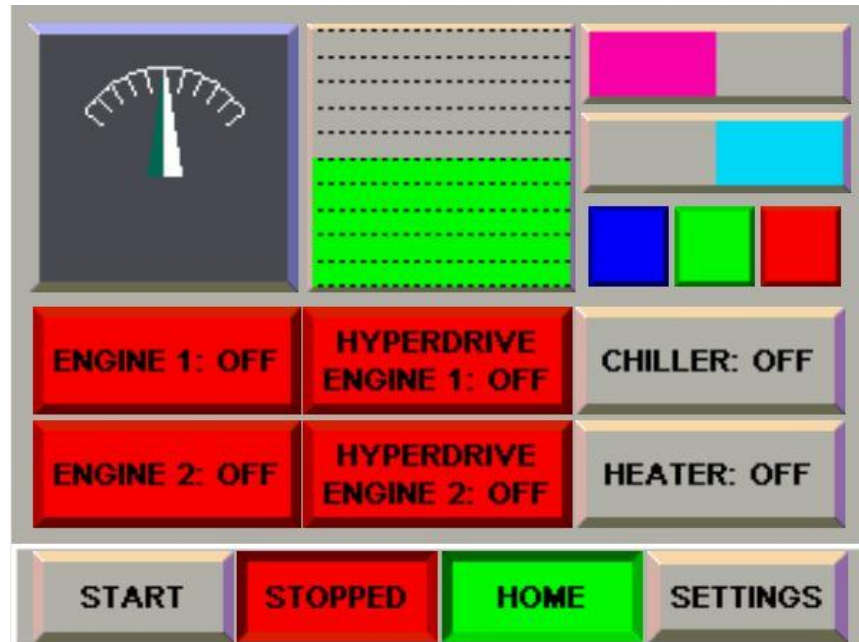
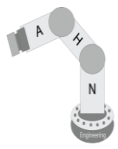


Figure 13: Play HMI Screen

The “Settings” screen allows the user to view the robot’s Cartesian coordinates, set the height, and radius of the robot in real time. See screen in Figure 14 below.



Figure 14: Settings HMI Screen



Communication

The system uses numerous different industrial protocols to communicate. Typically, it is preferred to stick with one protocol but due to the supplies being donated by outside sources, it was not in our control to dictate what protocols were available. The Computer Vision system communicates over Ethernet to the PLC using a python library called Pycomm by Ruscito. ^[3] This setup does not require the PLC to have a configured device within its Ethernet tree. The HMI communicates with the PLC with serial communication. The null modem serial cable between the two allows them to communicate. Despite the HMI being programmed over Ethernet and Ethernet/IP capable, the HMI cannot communicate over Ethernet with a CompactLogix PLC. The HMI can only communicate to older models of Allen Bradley PLCs. The PLC (Ethernet/IP) communicates to the Kuka Robot (EtherCAT) by communicating through an Anybus converter. The Anybus converter allows the Ethernet/IP device to communicate to an EtherCAT device with little lag.

The list of IP Addresses is shown below in Figure 15.

NAME	IP Address
PLC	192.168.1.150
C600 HMI	192.168.1.151
Fanuc Robot	192.168.1.154
Anybus Converter	192.168.1.155
Desktop	192.168.1.160
Kuka Robot	192.168.1.161
Nathan's Laptop	192.168.1.241

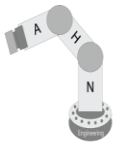
Figure 15: IP Address

An example of the output terminal is shown below in Figure 16.

```
TX_Angle
21.742032252277006
Opening Connection To PLC...
*****
PLC_Known_Head_Angle: 21
Head_Angle_Current: 21
NEW PLC_Known_Head_Angle: 21
Closing Connection...
*****

TX_Angle
23.37643821124763
Opening Connection To PLC...
*****
PLC_Known_Head_Angle: 21
Head_Angle_Current: 23
NEW PLC_Known_Head_Angle: 23
Closing Connection...
*****
```

Figure 16: Terminal Output



Manufacturing

The system requires custom parts to be manufactured such as camera mounts, foam mounts, high voltage covers, Ethernet switch mount, and PCB. These parts are manufactured using Nathan's 3D Printer and CNC machine. The parts are developed in Autodesk Fusion for 3D Printing and Autodesk Eagle for the printed circuit boards.

The camera mount is made with blue PLA filament shown in Figure 17 below. The mount is designed to hold the Logitech C910 Camera and mount to the top of the control panel with 3mm bolts. The camera can be strapped into the with a small zip tie through the slots along the side and through the camera's folding stand.

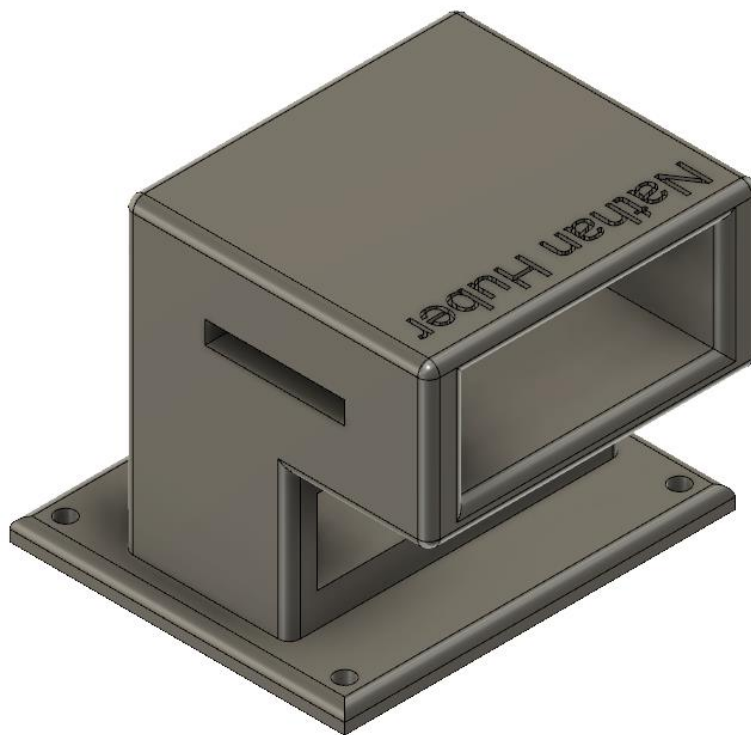
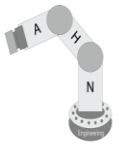


Figure 17: Camera Mounts



The foam mounts are made with blue PLA filament shown in Figure 18 below. The foam mounts are designed to be the same diameter as the foam tubes that will be interested into them. The inner side of the mount has a protruding notch that digs into the foam tube to ensure that it does not move. The mounts are affixed to the control panel with self-tapping sheet metal screws. The foam provides a cushion for any accidental impacts to the side of the control panel.

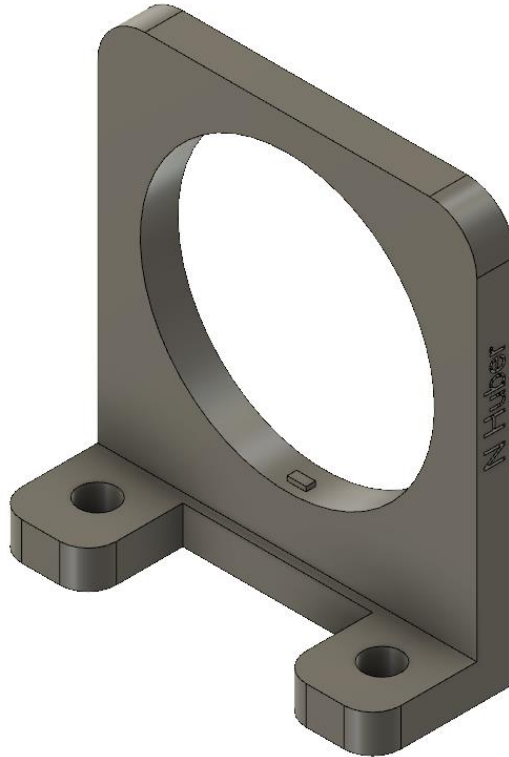
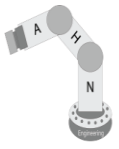


Figure 18: Foam Mounts



The high voltage covers are made with purple PLA filament shown in Figure 19 and Figure 20 below. The high voltage covers protect users and conductive materials from coming into contact with 120VAC that is used within the main control panel.

The cover shown in Figure 19 below, protects the main 120VAC fuse terminals. This fuse protects the incoming line of the Sola 24VDC power supply. The voltage cover has a small cutout along the rear to fit over din rail. Slots along the top and bottom allow incoming and outgoing cables to fit between the PLC and the cover. Horizontal slots along the front face allow the user to see if the fuse has blown. When a fuse failure has occurred, a red light will illuminate on the fuse holder and shine through the slots.

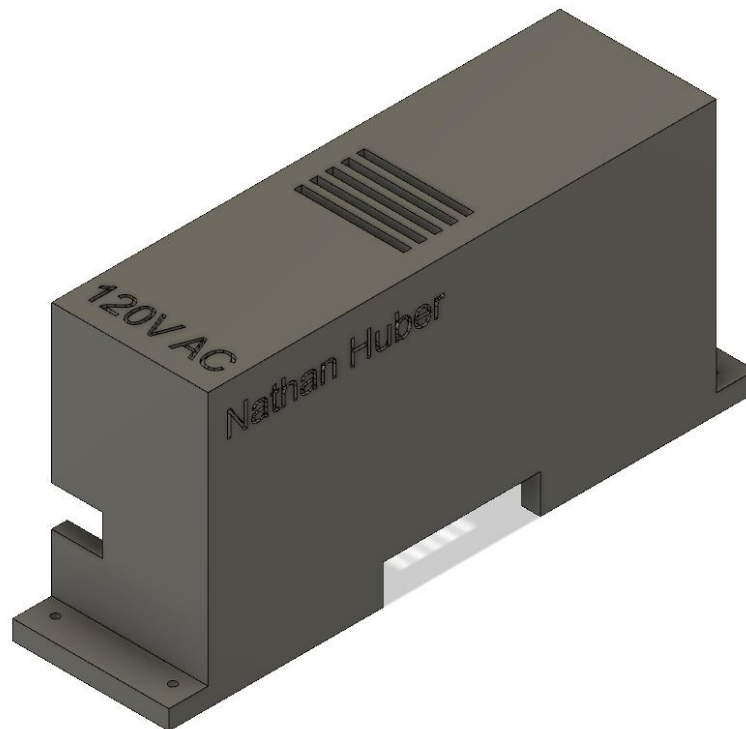
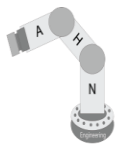


Figure 19: Circuit Breaker Cover



The cover shown below in Figure 20, protects the Sola Power Supply terminals from being touched. The voltage cover has holes at the top and bottom of the right-hand side tabs to be affixed to the power supply with screws.

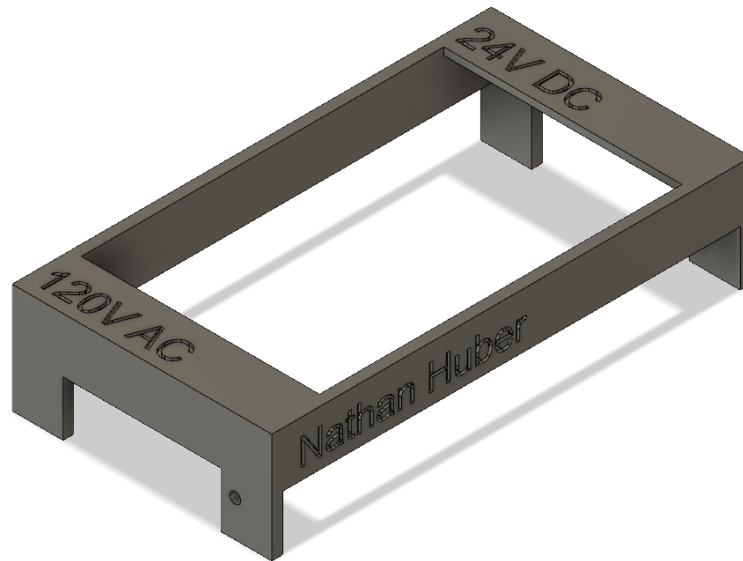


Figure 20: Sola Power Supply Cover



The Ethernet switch mount is made with purple PLA filament shown in Figure 21 below. The TP-Link 8 Port Ethernet switch snaps into place through an opening on the side of the part. The opening is slightly larger than the thickness of the Ethernet Switch. The bottom of the opening has a slight lip for the Ethernet switch to hold the switch into place once inserted all the way. On the opposite side, there is a small square opening to allow the 12VDC plug to be inserted into the device. The rear of the mount has two screw holes that have a large enough width between them for the screws to be inserted through the slots within the din rail. This allows the Ethernet switch mount to be mounted on top of din rail with screws. A major flaw in this design is that for the mount to be removed, the Ethernet switch must be unplugged and removed to relocate the mount.

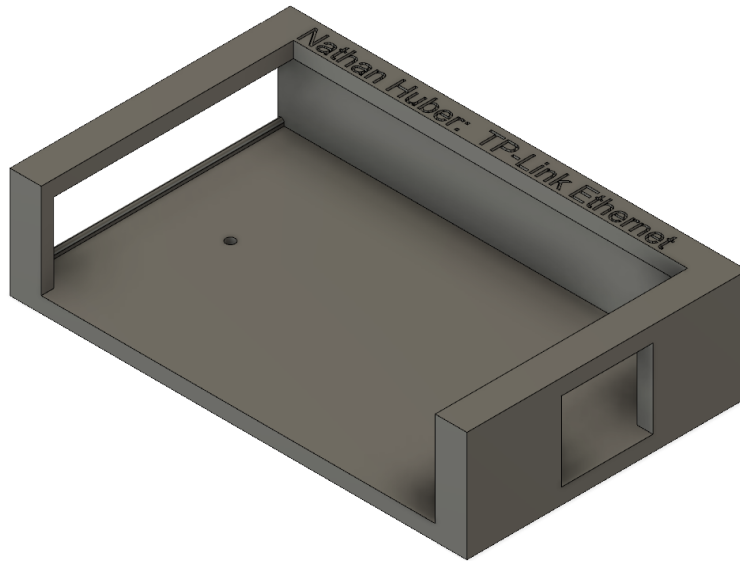
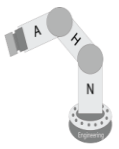


Figure 21: Ethernet Switch Mount



Robotic Flight Simulator

The PCBs were designed to expand the amount of IO available to the Arduino Nano and to regulate 24 VDC to 5 VDC for use throughout the entire panel. Each component and point are through-hole soldered. Design considerations included extra IO and the option of a physical pull-up resistor rather than the internal pull-up implemented with the IO expander chip. The schematics and PCB layouts are shown in Figure 22, Figure 23, Figure 24, and Figure 25.

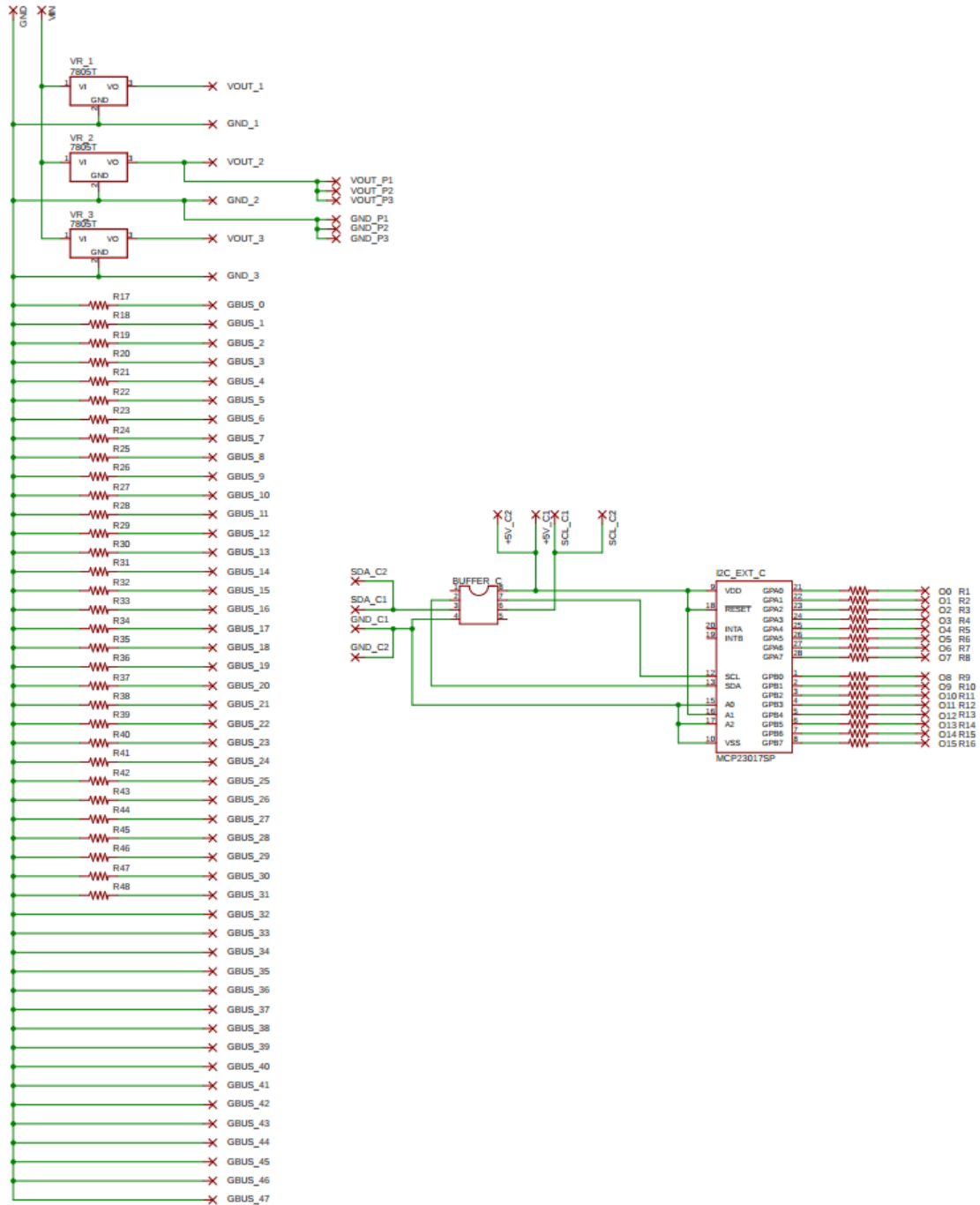


Figure 22: Power and Output PCB Schematic

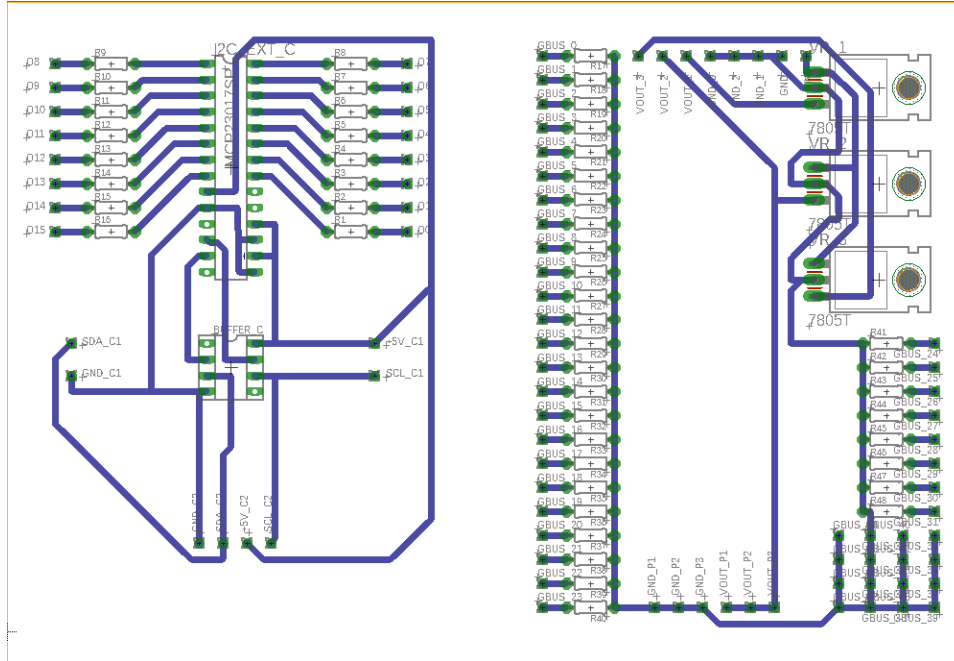


Figure 23: Power and Output PCB Layout

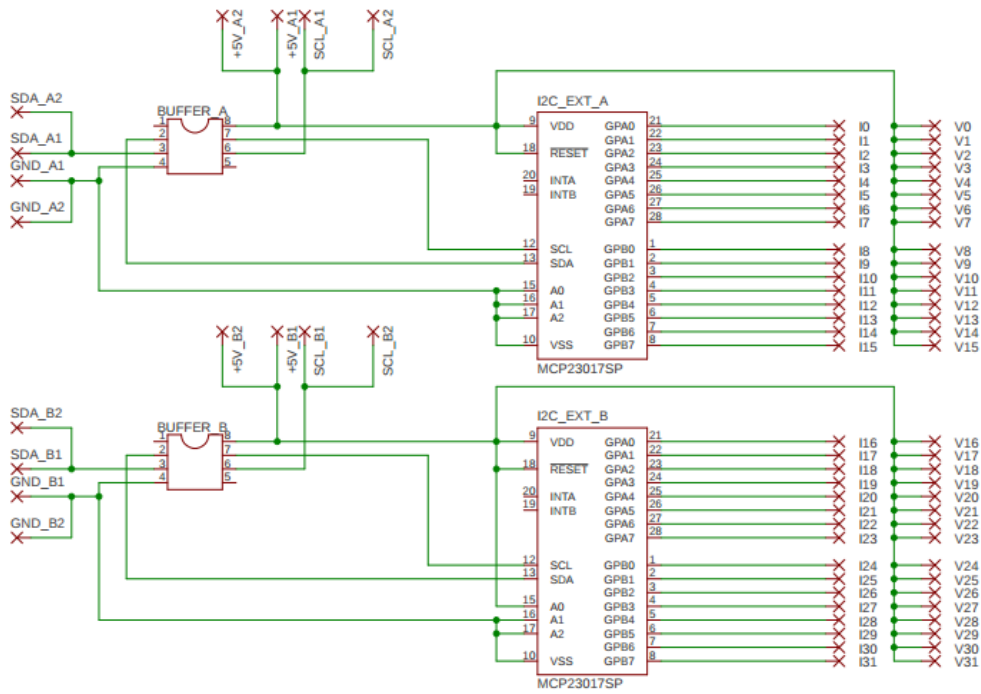
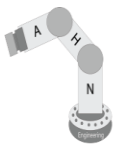


Figure 24: Input PCB Schematic

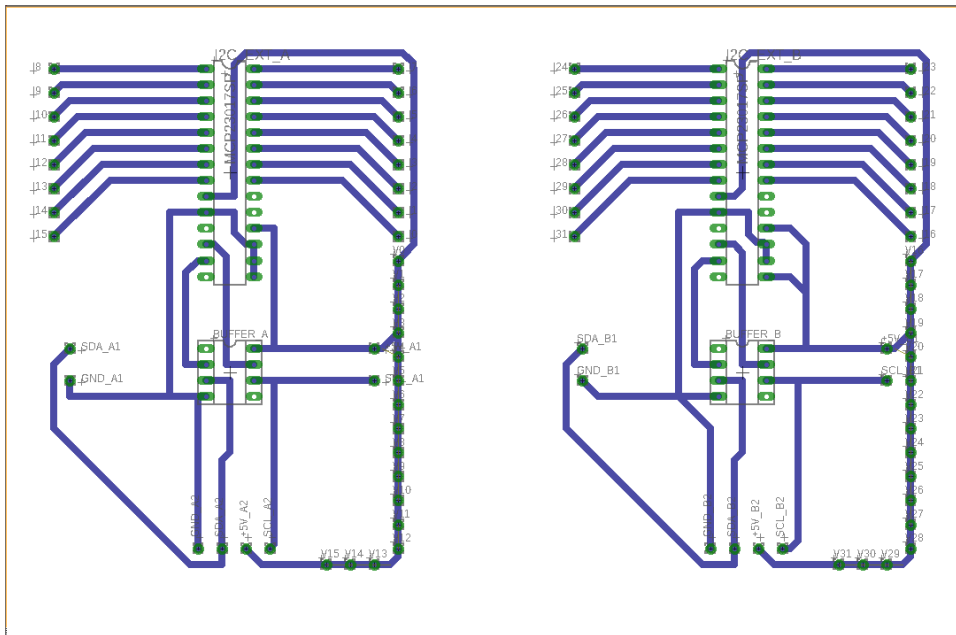
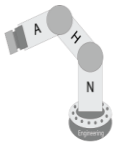


Figure 25: Input PCB Layout



The printed circuit boards are cutout from a 6" x 6" copper clad board. The PCB schematics and board are designed in Autodesk Eagle. The software FlatCAM and bCNC are used to prepare and control the CNC milling process. The CNC uses a 3.175mm end mill to cutout the board and a 0.2mm end mill to mill the traces. A benchtop drill press was used to drill the through-holes. See Figure 26 below to see the boards post milling process.

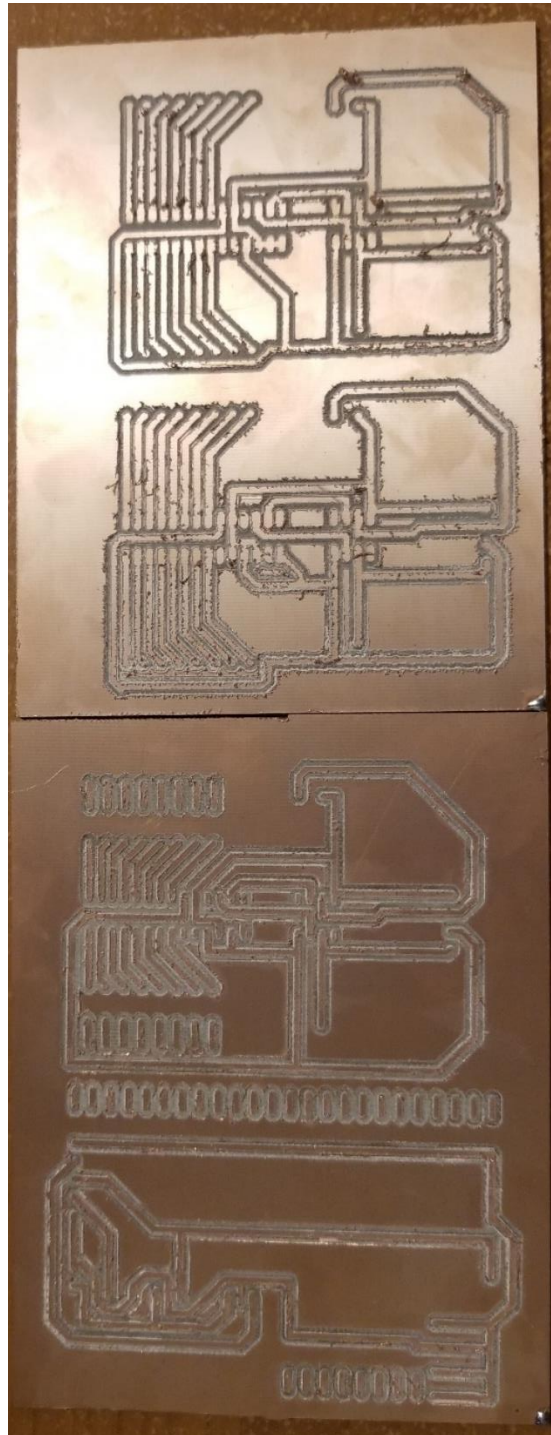
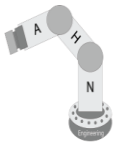


Figure 26: Post CNC Milling



Safety

The project will utilize numerous safety measures to protect the equipment and the personnel using it. The robot will maintain a minimum of 24 inches away from any stationary object to meet the ISO Robotic Standard. There will be an E-Stop that is tied into the robot's safety processor to halt motion. The robot is collaborative, allowing the robot to stop safely when colliding with a human. The robot is configured for a stopping force of 30N. In order to have the Kuka robot at public events and have the public be able to interact with the robotic system, Nathan co-authored the robotic safety guidelines for the EH&S department and the College of Engineering. These reports are appended to the end of this document. For brevity, the following are in place for the system to operate safely.

- High visibility duct tape showing the robots' maximum reach.
- Sign(s) warning of robot motion.
- Configuring limits internal to the robot.
- Foam attachments around the End Effector (Control Panel) to reduce hard edges.
- The Blue LED Ring Light will illuminate prior to the motion.
- Nathan will hold the Teach pendant for an E-Stop
- There is a red button on the robot's control panel that will pause the robot.

Nathan designed the layout of the lab in Roboguide and Autodesk Electrical for the installation of the Fanuc robot and to visualize the DCS parameters. DCS stands for Dual Check Safety and is the safety component of the Fanuc robot. The DCS is configured to setup workable areas, collaborative settings, payloads, and user models. In Figure 27 below is a screen shot taken from the Roboguide model.

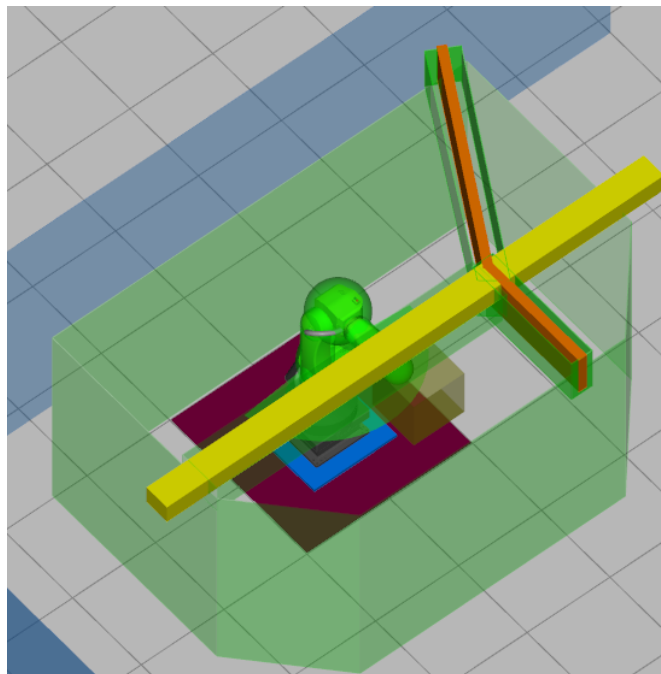


Figure 27: Roboguide Simulator



Budget

The breakdown of the budget is shown below in Figure 28 to Figure 30. Most of the supplies will be provided by Austin and Nathan and the remaining supplies will be purchased using the money allotted by the College of Engineering.

Senior Design: Robotic Flight Simulator (1/3)										
Bill of Material										
Members: Nathan H, Austin K, & Heath P										
Line Item:	Qty:	Catalog Number:	Description:	Manufacturer:	Vendor:	Supplier:	Unit Cost:	University Funded	Personally Funded	Total Cost:
1000	1	CR35-IA	Fume Robot	Fume	Fume America	University of Cincinnati	\$45,710.00	\$45,710.00		\$45,710.00
1001	1	Software Options	Robot Software Additions	Fume	Fume America	University of Cincinnati	\$9,828.90	\$9,828.90		\$9,828.90
1002	1	R820-14	Kuka iiva	Kuka	Kuka	University of Cincinnati	\$50,000.00	\$50,000.00		\$50,000.00
1003	1	C600	AB HMI 6"	Allen Bradley	Rockwell	University of Cincinnati	\$500.00	\$500.00		\$500.00
1004	1	1769-L23E-QB1B	Compact Logix PLC	Allen Bradley	Rockwell	University of Cincinnati	\$1,200.00	\$1,200.00		\$1,200.00
1005							\$0.00	\$0.00		\$0.00
1006	1	Logitech - C920 Web Cam	C920 Web Cam	Logitech	Logitech	Heath Palmer	\$50.00	\$50.00		\$50.00
1007							\$0.00	\$0.00		\$0.00
1008	2	A-1640	Rotary Switch 4 Pole 3 Position	Tayda Electronics	Tayda	Austin Kucinski	\$0.89	\$0.89		\$1.78
1009	3	A-5098	Black Plastic Knob with Green Pointer	Tayda Electronics	Tayda	Austin Kucinski	\$0.22	\$0.22		\$0.66
1010	5	A-322	Black Plastic Knob with White Pointer	Tayda Electronics	Tayda	Austin Kucinski	\$0.22	\$0.22		\$1.10
1011	3	A-1962	1K OHM Linear Taper Potentiometer	Tayda Electronics	Tayda	Austin Kucinski	\$0.50	\$0.50		\$1.50
1012	5	A-706	LED 5mm Red	Tayda Electronics	Tayda	Austin Kucinski	\$0.02	\$0.02		\$0.10
1013	5	A-057	LED 5mm Green	Tayda Electronics	Tayda	Austin Kucinski	\$0.03	\$0.03		\$0.15
1014	5	A-407	LED 5mm Blue	Tayda Electronics	Tayda	Austin Kucinski	\$0.05	\$0.05		\$0.25
1015	5	A-1583	LED 5mm Yellow	Tayda Electronics	Tayda	Austin Kucinski	\$0.03	\$0.03		\$0.15
1016	5	A-4567	Mini Toggle Switch SPDT On-On	Tayda Electronics	Tayda	Austin Kucinski	\$0.47	\$0.47		\$2.35
1017	3	A-179	LM7805 Voltage Regulator	Tayda Electronics	Tayda	Austin Kucinski	\$0.23	\$0.23		\$0.69
1018	50	A-2115	10K OHM 1/4W 5% Resistor	Tayda Electronics	Tayda	Austin Kucinski	\$0.01	\$0.01		\$0.50
1019	5	A-001	8 pin DIP IC Socket Adaptor	Tayda Electronics	Tayda	Austin Kucinski	\$0.03	\$0.03		\$0.15
1020	5	A-1601	28 pin DIP IC Socket Adaptor	Tayda Electronics	Tayda	Austin Kucinski	\$0.11	\$0.11		\$0.55
1021	1	A-5162	Copper Clad Board PCB	Tayda Electronics	Tayda	Austin Kucinski	\$1.89	\$1.89		\$1.89
1022	20	A-2119	220 OHM 1/4W 5% Resistor	Tayda Electronics	Tayda	Austin Kucinski	\$0.01	\$0.01		\$0.20
1023	10	A-2067	330 OHM 1/4W 5% Resistor	Tayda Electronics	Tayda	Austin Kucinski	\$0.01	\$0.01		\$0.10
1024	16	A-2940	PCB support with Adhesive Back	Tayda Electronics	Tayda	Austin Kucinski	\$0.10	\$0.10		\$1.60
1025	1	A-2849	Knurled Aluminum Black Knob	Tayda Electronics	Tayda	Austin Kucinski	\$1.29	\$1.29		\$1.29
								\$107,288.90	\$107,288.90	\$107,288.90
								\$288.87	\$288.87	\$382.80
								\$288.87	\$288.87	\$382.80
								\$107,577.77	\$107,577.77	\$107,671.70

Figure 28: Bill of Material (1/3)



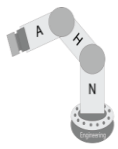
Senior Design: Robotic Flight Simulator (2/3)									
Bill of Material									
Members: Nathan H, Austin K, & Heath P									
Line Item:	Qty:	Catalog Number:	Description:	Manufacturer:	Vendor:	Supplier:	Unit Cost:	University Funded	Total Cost:
1026	1	A-4557	Knob DAVIES 1900H CLONE Red	Tayda Electronics	Tayda	Austin Kucinski	\$0.42		\$0.42
1027	1	A-389	Davies 1510 Clone Red Knob	Tayda Electronics	Tayda	Austin Kucinski	\$0.42		\$0.42
1028	1	-	0.56" 4-Digit 7-Segment Display Bezel	Tindie	Tindie	Austin Kucinski	\$4.99		\$4.99
1029	6	-	16mm push button LED square blue	BENKPAK	AliExpress	Austin Kucinski	\$1.10		\$6.60
1030	1	1442	16mm LED push button red latching	Adafruit	Adafruit	Austin Kucinski	\$1.50		\$1.50
1031	1	559	Metal pushbutton Red LED Ring	Adafruit	Adafruit	Austin Kucinski	\$4.95		\$4.95
1032	1	a17031000ux0114	Emergency Stop Push Button	Uxcell	Amazon	Austin Kucinski	\$9.99		\$9.99
1033	1	CXCP212C	Red Cover Rocker Toggle Switch 5	ESUPPORT	Amazon	Austin Kucinski	\$10.19		\$10.19
1034	1	B016RG9OGQ	7-segment Display W/2c Backpack	Adafruit	Amazon	Austin Kucinski	\$12.12		\$12.12
1035	1	-	I2C Bus Extender/Buffer pack of 5	FXI Electronics	AliExpress	Austin Kucinski	\$3.67		\$3.67
1036	10	593-3210C	VCC Clear Fresnel 5mm / LED Lenses	VCC	Mouser	Austin Kucinski	\$0.46		\$4.56
1037	10	593-RNG268	VCC RETAINING RING	VCC	Mouser	Austin Kucinski	\$0.24		\$2.37
1038							\$0.00		\$0.00
1039							\$0.00		\$0.00
1040	2	PCB	Circuit Board	Tayda Electronics	Tayda	Nathan Huber	\$2.99		\$5.98
1041	1	-	Main Electrical Control Panel	-	-	Nathan Huber	\$25.00		\$25.00
1042	1	-	Hardware (Bolts, Screws, Wire Ties)	-	-	Austin & Nathan	\$25.00		\$25.00
1043	1	-	Steel (EOAT Panel Mount)	-	-	Nathan Huber	\$50.00		\$50.00
1044	1	-	DIN Rail pack of 5	AliExpress	AliExpress	Austin Kucinski	\$6.64		\$6.64
1045	3	RT18-32X	10x38mm DIN Rail Mount Fuse Holder	May's	AliExpress	Austin Kucinski	\$1.52		\$4.56
1046	5	C10G2	Fuse, 2A, 10X39mm	Bussman/Eaton	Newark	Austin Kucinski	\$0.98		\$4.90
1047	2	C10G4	Fuse, 4A, 10X39mm	Bussman/Eaton	Newark	Austin Kucinski	\$1.72		\$3.44
1048	1	-	Wire tube	-	Home Depot	Austin Kucinski	\$2.00		\$2.00
1049	2	-	Charcoal Spraypaint	Rustoleum	Home Depot	Austin Kucinski	\$4.00		\$8.00
1050							\$0.00		\$0.00
							University Funded:	\$107,288.90	\$107,288.90
							Personally Funded:	\$288.87	\$382.80
							Group:	\$288.87	\$382.80
							Total Cost:	\$107,577.77	\$107,671.70

Figure 29: Bill of Material (2/3)



Senior Design: Robotic Flight Simulator (3/3)									
Bill of Material									
Members: Nathan H, Austin K, & Heath P									
Line Item	Qty	Catalog Number	Description	Manufacturer	Vendor	Supplier	Unit Cost	University Funded	Total Cost
1051	1	1	Null Modem Cable 10ft	Generic	Amazon	Nathan Huber	\$0.00	\$0.00	\$0.00
1052	7	Generic	Ethernet Cables	Generic	Amazon	Nathan Huber	\$7.39	\$7.39	\$7.39
1054	1	Generic	16 Awg Wiring	Generic	Amazon	Nathan Huber	\$20.00	\$20.00	\$49.00
1055	1	Generic	16 Awg Wiring - 4 Cond	Generic	Amazon	Nathan Huber	\$20.00	\$20.00	\$20.00
1056	70	A-4995	AWG 22 White Wire 1FT (30cm) Solid	Tayda Electronics	Tayda	Austin Kucinski	\$0.09	\$0.09	\$6.30
1057	70	A-4999	AWG 22 Blue Wire 1FT (30cm) Solid	Tayda Electronics	Tayda	Austin Kucinski	\$0.09	\$0.09	\$6.30
1058	5	A-4902	20cm Blue Heat Shrink Tubing 1.5mm	Tayda Electronics	Tayda	Austin Kucinski	\$0.10	\$0.10	\$0.50
1059	5	A-4905	20cm White Heat Shrink Tubing 1.5mm	Tayda Electronics	Tayda	Austin Kucinski	\$0.10	\$0.10	\$0.50
1060	5	A-4909	20cm Blue Heat Shrink Tubing 3.5mm	Tayda Electronics	Tayda	Austin Kucinski	\$0.10	\$0.10	\$0.50
1061	5	A-4912	20cm White Heat Shrink Tubing 3.5mm	Tayda Electronics	Tayda	Austin Kucinski	\$0.10	\$0.10	\$0.50
1062	5	A-4918	20cm Black Heat Shrink Tubing 6mm	Tayda Electronics	Tayda	Austin Kucinski	\$0.14	\$0.14	\$0.70
1063	5	A-4931	20cm Green Heat Shrink Tubing 10mm	Tayda Electronics	Tayda	Austin Kucinski	\$0.16	\$0.16	\$0.80
1064	5	A-4911	20cm Black Heat Shrink Tubing 3.5mm	Tayda Electronics	Tayda	Austin Kucinski	\$0.10	\$0.10	\$0.50
1065	1	Generic	3D PLA Filament	Generic	Amazon	Nathan Huber	\$20.00	\$20.00	\$20.00
1066	1	TP-Link 8 Port	Ethernet Switch	TP-Link	Amazon	Nathan Huber	\$15.00	\$15.00	\$15.00
1067	1	SDN 5-24-100	24V Power Supply	Sola	Ebay	Nathan Huber	\$22.50	\$22.50	\$22.50
1068	1	Generic	USB Extension	Generic	Amazon	Nathan Huber	\$0.00	\$0.00	\$0.00
							University Funded:	\$107,288.90	\$107,288.90
							Personally Funded:	\$288.87	\$382.80
							Group:	\$288.87	\$382.80
							Total Cost:	\$107,577.77	\$107,671.70

Figure 30: Bill of Material (3/3)

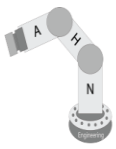


Robotic Flight Simulator

The hourly breakdown shown in Figure 31 assumes that the rate per hour is \$100.

Category	Estimated	Actual	Category	Estimated	Actual
Eye Tracking			Robotic Programming (Kuka & Fanuc)		
Market Research	10	10	Purchasing	15	22
Literature Review	10	8	Shipping/Install	10	85
Integration Research	10	10	Software Programming	50	48
Hardware Setup	25	15	Wire Assembly	10	9
Software Setup	25	40	Communication & IO	2	8
Troubleshooting	16	12	Initial Startup	10	10
Mount Construction	2	2	Debug	25	18
System Integration	16	10	Total:	122	200
Total:	114	107	PLC Programming		
Control Panel			Software Programming	30	20
Control Panel Hardware Design	20	5	Communication & IO	2	1.5
EOAT Panel Hardware Design	20	15	Debug	10	1.75
Control Panel Assembly	40	20	Total:	42	23.25
EOAT Panel Assembly	40	65	HMI Programming		
PCB Manufacturing(EOAT & Control)	15	30	Software Programming	25	19
Arduino Programming	20	25	Communication & IO	2	1.75
Debug	30	30	Debug	10	2
Total:	185	190	Total:	37	22.75
Presentations			Total Project		
Technical Design Reviews (Oral)	20	2	Total Hours:	580	570
Construct Poster	40	10	Labor Rate:	\$100	
Tech Expo	20	15	Total Cost:	\$58,000	\$57,000
Total:	80	27			

Figure 31: Hourly Breakdown



Timeline

With a capstone project of this size, the timeline is rushed. It is anticipated to have all hardware and software completed promptly after Christmas break. Integration and debug will start at the beginning of January. The estimated timeline is shown in Figure 32 below. The Gantt chart does not follow the typical downward stair step pattern because each team member will play a key role within the development of the project while working independently.

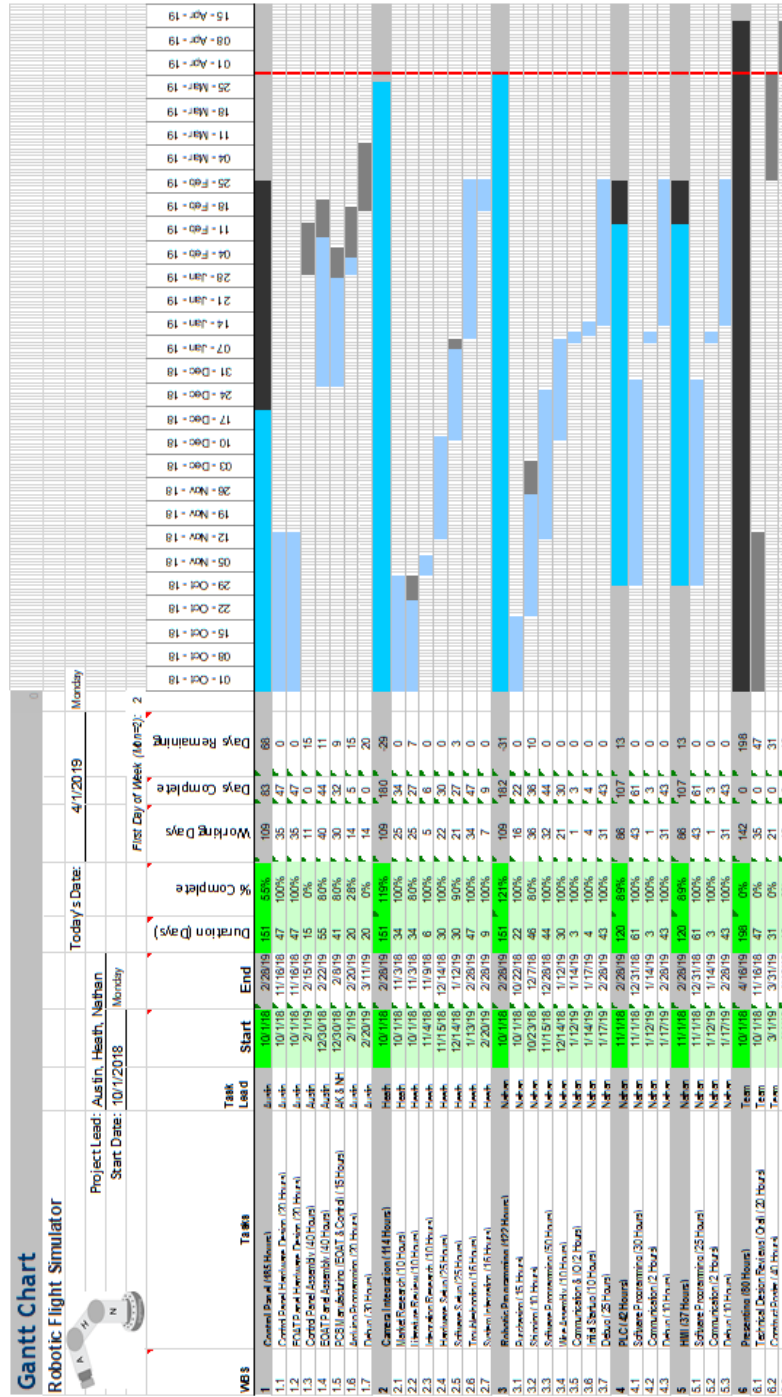
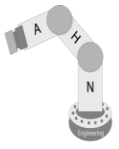


Figure 32: Timeline



Lessons Learned

The following section describes the lessons learned throughout the project. It will cover different issues that occurred and the resolutions to them.

HMI

Originally, the plan for the HMI was to communicate over Ethernet/IP to the PLC. This would allow for all of the network to be on an Ethernet based protocol. Instead, a null-modem serial cable is used to establish communication between the PLC and HMI.

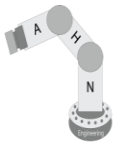
Early in the design phase, it was thought that having a PanelView 5300 series HMI on the control panel would be ideal to act as the “Settings” screen and the C600 would only be the “Play” screen. It was found that the newer PanelView HMI’s could not communicate to the CompactLogix PLC’s due to device version conflicts.

Robot

The robot intended to be used was Fanuc CR35iA shown in Figure 33 below.



Figure 33: Fanuc Robot



Robotic Flight Simulator

The Fanuc robot was received late December. Upon arrival, the robot was found to be too tall for the lab's doorway and hallway. The pallet it was shipped on had too wide of fork lift pockets for the robot to be lifted with the small forklift at hand. Fanuc employees came to assist Nathan and the universities facility employees in moving the robot by bringing a device called a "Brake Box" that allows the robot's brakes to be released and the arm moved. This allowed for the robot's arm to be lowered for transportation through the hallway. By using pallet jacks the robot was able to be transported into the lab. The lab's concrete is only five inches thick and Fanuc recommends a minimum of eight inches of concrete. Nathan worked with the universities structural engineer and facilities manager on figuring out a way to install the robot. It was decided that a larger 6.5ft plate will go underneath the robot to redistribute the forces applied to floor. Early to mid-April the Fanuc robot installation process started. See Figure 34 below.

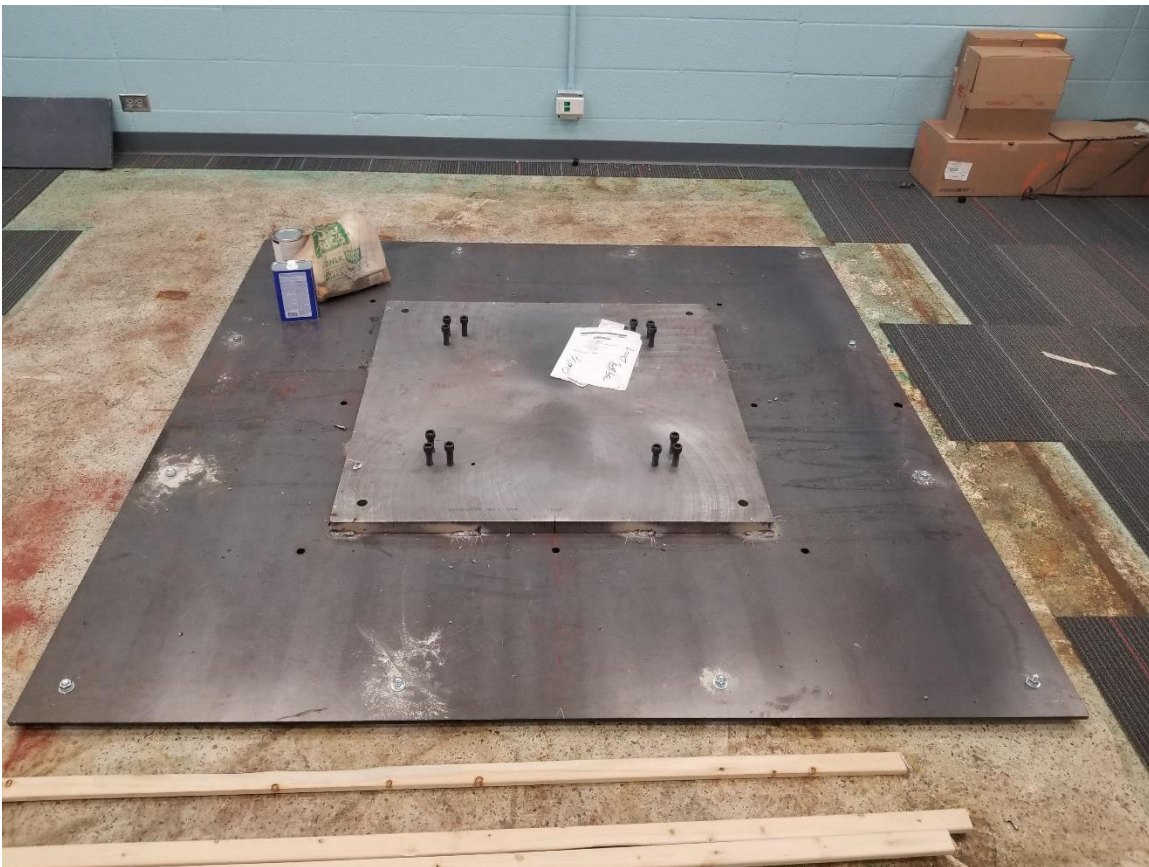
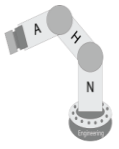


Figure 34: Fanuc Installation Base

With the major delay and hold-ups with the Fanuc robot, Nathan taught himself Kuka robotics over winter to ensure the robotic portion did not fall behind. It was found that the University operates differently than an industrial facility Nathan is familiar with.



Control Panel

Aesthetically and operatively speaking, the control panel preformed perfectly as design specifications were laid out and dictated. It adequately mimicked an aircraft control panel and the more popular button mechanics were implemented. Where the most changes would be made deal with the design of the PCBs and ultimately the cable management within the control panel. The first change would be to implement terminal blocks at the points that connect to external wiring such as inputs and outputs. This would have eased installation and ultimately saved time and space. The second change would be to layout the boards differently to improve the ability to cable manage. At the first revision of the boards, the amount of IO and other considerations had to be made without knowing the final layout of the physical setup and design. Now that these considerations are finalized, the PCBs could be trimmed and re-laid out to improve cable management within the panel.

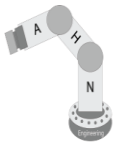
Vision

While testing the system with various people, it was found that people with a skinnier and more oblong face cause inaccuracies within the vision system. Also, it depended on if the user was wearing glasses or not. The vision system identifies points around the eyes, eyebrows, nose, mouth, and jawline. When the user's face is skinnier, the points identified become too close together for the system to estimate the head angle accurately. If the user was wearing glasses, the points around the eyes and eyebrows would be identified along the rim of the glasses or the glare reflecting from the lenses. The vision system also has issues with numerous faces being within the field of view. This causes the identified face to jump around between the faces detected. These results are concluded from Nathan's observations of the numerous users at the CEAS Tribunal Expo.

The original plan was to use a Raspberry Pi, but it was found that the processing power of the units are not enough for the task required. Nathan found that there is approximately a four second lag between the image being parsed to transmission. A 20mm fan was added to cool the CPU but provided little help to the Raspberry Pi's speed. It did reduce the temperature of the CPU but did not improve the speed noticeably.

Future Recommendations

This project is not a complete solution to something rather a step towards improved human – robot collaboration. The project integrates many rapidly growing fields such as industrial control, robotics, and vision. In the future, it is hoped to have an improved vision system and a virtual reality component added to it.



CONCLUSION

Benefactors

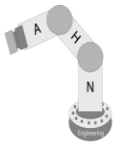
Many people will benefit from the Robotic Flight Simulator project. It will help reduce the costs of training pilots. Also, the community as a whole will benefit from the increased research into the relationship between humans and robotics. It cannot accurately be estimated on the total reduction of costs because of the new technology being used.

Conclusion

In conclusion, The Robotic Flight Simulator will provide a cheaper method of simulating airplane controls and improve the human - robotics relationship. The objective of the project was completed, to create a robotic system that responds to human feedback. This feedback is in the form of the user's head angle from a custom vision system. This is not a final project that has officially solved an issue but is a step towards improving human – robot relations.

References

- 1) Fly Away [Internet]. [cited 2018 October 27]. Available from: <https://flyawaysimulation.com/news/4492/>
- 2) Head Pose Estimation [Internet]. [cited 2019 April 11]. Available from: <https://github.com/lincolnhard/head-pose-estimation>
- 3) Pycomm [Internet]. [cited 2019 April 11]. Available from: <https://github.com/ruscito/pycomm>
- 4) Full-Flight Simulators [Internet]. [cited 2018 November 11]. Available from: <https://www.virtual-aerospace.com/full-motion-a320-flight-simulator/>



APPENDIX

Appendix A: HMI Program

Website: <https://github.com/naterbug25/Capstone/tree/master/HMI>

Appendix B: PLC Program

Website: <https://github.com/naterbug25/Capstone/tree/master/PLC>

Appendix C: Vision Program

Website: https://github.com/naterbug25/Capstone/tree/master/Computer_Vision

Appendix D: Computer <--> PLC Communication Program

Website: https://github.com/naterbug25/Capstone/tree/master/Computer_PLC_Comm

Appendix E: Robot Main Program

Website: https://github.com/naterbug25/Capstone/tree/master/Robot_Program

Appendix F: Robot Background Program

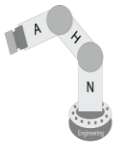
Website: https://github.com/naterbug25/Capstone/tree/master/Robot_Program

Appendix G: 3D Print STL Files

Website: https://github.com/naterbug25/Capstone/tree/master/3D_Print_STL

Appendix H: Datasheets

Website: <https://github.com/naterbug25/Capstone/tree/master/Datasheets>



Appendix I: EH&S Robotic Safety Procedure



Robotic Safety Guidelines

UC-Office of Environmental Health & Safety

Presented by:

Jan-Arthur, Nathan Huber, Dr. Ma, Dr. Pinelo

Date: April 01, 2019



Purpose:

The UC-Office of Environmental Health & Safety (UC-EH&S) has developed this Robotic Safety Plan to establish minimum requirements for the design, rebuild, installation, safeguarding, maintenance, testing, start-up and employee/user training as it relates to, or use of robots or robotic systems. This UC-EH&S safety plan on robotic systems requires that all robots and robotic systems are operated in accordance with the International Organization for Standardization ISO10218, and other applicable federal 29 CFR 1910.212 and state regulations established for the safe construction and operation of the equipment.

Scope:

This program applies to all University of Cincinnati employees and students who design, install, operate and service academic robotic systems.

Responsibilities:

Responsibility for safety rests at all levels including:

Office of Environmental Health & Safety

- To provide consultation and administer periodic routine audits to ensure the proper safeguarding and use of robots and robotic systems.
- To provide information and general safety training of environmental health and safety practices for all Principal Investigators, students, and staff.
- To investigate incidents or emergencies.
- Perform hazard assessments for the robotic equipment.

Principal Investigator (PI) or Lab Supervisor

- To ensure all staff and students are trained and have learned safety requirements and safe rules prior to entering the robot facility unsupervised and to provide project specific training.
- To write Standard Operating Procedures (SOPs) and completing risk assessments and forwarding the assessments to UC-EH&S for review.
- To establish safeguards (i.e. barrier fences, interlocked gates, emergency stops, pendants) in place and are operational at all times (when required by the risk assessment).
- Safeguarding and controlling robot keys (if required).
- To respond to any incidents or emergencies.
- To cooperate with the UC-Office of Environmental Health & Safety for periodic audits.

Robot Users

- Completing required training and keeping all training up-to-date.
- To comply with this Robotic Safety Plan and the associated SOPs.
- To wear appropriate Personal Protective Equipment if required by safety plan.
- To ensure safe work practices when the PI or the Lab Supervisor is not present.
- To operate the robot and robotic systems as intended for.
- To report any incidents, emergencies, or defective equipment to their supervisor or PI and the Office of Environmental Health & Safety



Visitors (spectators)

A spectator is defined as an individual who wishes to observe or watch the robot or the robotic system in operation and may lack the appropriate robot training.

As required by the Safety Responsibilities Policy, and the Robotic Program, all personnel not directly associated with the robot facility, guests, contractors or non-laboratory personnel visiting or wishing to enter the robot facility (spectators) must first obtain permission from the Principal Investigator or Lab supervisor prior to accessing the facility, the degree of hazard and avoidance procedure must be explained to them, and appropriate protective measures taken.

Hazard Identification and Risk Assessment:

At each stage of design and installation of a robot and robotic system, a hazard identification and risk assessment as well as personnel safeguarding requirements shall be performed (as described in Section 4.0 of the ISO 10218-2:2011(E)). The appropriate level of safeguarding determined by the hazard identification and risk assessment shall be applied prior to operation. In addition, the risk assessments for each stage of development shall be documented and remain with the robot and robotic system for reference.

Safeguards:

When design does not either remove the hazards or adequately reduce the risks, and the risk assessment indicates a need, safeguarding shall be applied (as described in Section 5.10 of the ISO 10218-2:2011(E)). Therefore, access to hazardous areas of the robot and robotic systems shall be protected by safeguards such as guards and protective devices.

Robot and robotic system guarding/safeguarding shall comply with Section 5 of the ISO 10218-2:2011(E) and contain the following minimum:

- Limiting robot motion as described in 5.4 of the ISO 10218-2:2011(E);
- Use of a key, plug or actuating device which is not easily duplicated or tamper-resistant;
- Supervisory control of spare keys and actuating devices;
- Barriers that cannot be defeated intentionally without the use of tools;
- Perimeter safeguarding as described in Section 5.5.1 of the ISO 10218-2:2011(E);
- Installation that cannot be placed in automatic operation until the associated safeguard is active as described in Section 5.6.3.3 of the ISO 10218-2:2011(E);
- Installation that will result in a shutdown of operations if the safeguard is removed while the hazard is present as described in Section 5.6.3.4 of the ISO 10218-2:2011(E);
- Installation will not result in an automatic re-start of operation as a result of only activating the safeguard as described in Section 5.6.3.4.2 of the ISO 10218-2:2011(E);
- Must be capable of being easily unlocked from the inside of the safeguarded space with or without power available, when the possibility of full body access exists.



Collaborative Workspaces:

When the design does remove the safety hazards or adequately reduce the risks, and the risk assessment indicates no need, safeguarding will not need to be applied (as described in Section 5.11.3 of the ISO 10218-2:2011(E)).

Robot and robotic system guarding/safeguarding shall comply with Section 5 of the ISO 10218-2:2011(E) and contain the following minimum:

- Limiting robot motion as described in 5.4 of the ISO 10218-2:2011(E);
- Use of a key, plug or actuating device which is not easily duplicated or tamper-resistant;
- Supervisory control of spare keys and actuating devices;
- The collaborative workspace shall be defined with floor markings, signs, etc.
- The collaborative workspace shall be such that the operator can easily perform all tasks and the location of the equipment and machinery shall not introduce any hazards.
- The robot location shall be installed to provide a minimum of 20 inches from the operating space of the robot as defined in Section 5.11.3 of the ISO 10218-2:2011(E).
- The robot will utilize power and force limiting, contact events between the collaborative robot and body parts of the robot as defined in Section 5.5.5.2 Contact Situations of the ISO/TS 15066:2016(E).

Protective Devices:

When protective devices such as pressure sensitive equipment (mats), light curtains, and laser scanners are required, they shall comply with Section 5.10.5 of the ISO 10218-2:2011(E).

Emergency Stop:

Every robot system, pendent, or cell shall have a protective stop function and an independent emergency stop function as described in Section 5.3.8 and 5.3.9 of part 2 of the ISO 10218-2:2011(E). These stops shall stop all robot motion and other hazardous functions in the cell or at the interface between cells and other areas of the workplace.

Suspension of Safeguards:

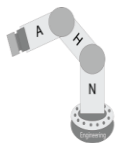
Tasks that require the suspension of safeguards shall have a dedicated mode of operation that automatically selects the appropriate safeguards, as determined by the risk assessment and as described in Section 5.10.11 of part 2 of the ISO 10218-2:2011(E).

Lockout/Tagout Procedures:

When entering a robot cell for any reason such as maintenance/servicing, un-jamming, or housekeeping, lockout/tagout procedures are required per the University of Cincinnati's Lockout/Tagout Program.

Initial Start-up Procedure Plan:

An initial start-up procedure plan for a new robot or robotic system shall be established that includes mechanical, electrical, and operational tests, with and without power being applied. These requirements are outlined in Section 5.12.3 of the ISO 10218-2:2011(E).



Training and Recordkeeping:

Training is a necessary and important part of the Robotic Safety Plan. See the SOPs for specific training requirements. All employees/students affected by this plan shall be trained in robots and robotic systems. The training requirements are outlined in Section 7.2 of part 2 of the ISO 10218-2:2011(E). This training shall include:

- General information from the Instructional Handbook.
- Handling as it related to transport, handling and storage.
- Installation and commissioning.
- Information for commissioning test or initial start-up procedure.
- Robot system information.
- Use of the robot system.
- Maintenance.
- De-commissioning.
- Emergency situations
- Robot specific information.

The UC-Office of Environmental Health & Safety offers Laboratory and Chemical Safety training programs. See the Pi or the Laboratory Supervisor for site specific training.

Personal Protective Equipment:

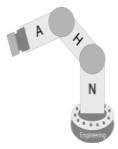
- Safety glasses
- Other SOP specific personal protective equipment

Fire Safety:

Only use a fire extinguisher if you have been trained to use one. In the event of a fire call 9-1-1. Notify your supervisor or Principal Investigator and UC-Office of Environmental Health & Safety of the fire.

Emergency Response:

In an emergency involving the robot, immediately report the events to your supervisor and UC-Environmental Health & Safety. For injury or medical emergency contact 9-1-1. Then contact your laboratory supervisor and UC-Environmental Health & Safety. Report any injuries with the Accident/Injury Form at <http://ehs.uc.edu/forms.asp>



Emergency Contacts:

Public Safety: 9-1-1
Non-Emergency Number: 556-1111
51 West Corry Street
Edwards Center III

Office of Environmental Health and Safety
Main Office: 513-556-4968
24/7 EHS On-call: 513-383-3242
51 Goodman Drive
University Hall Suite 260

University Health Services
Main Office: 513-556-6655
West Campus: 513-556-2564
Lindner Athletic Center
2751 O'Varsity Way, 3rd floor



Prior to Demo Check List

- 1) Visual Displays
 - Place 2 orange safety cones at the outer edge of the robot's defined work envelope.
 - Each cone will have an 8.5x11 sign stating robot is in motion.
 -) See sign on page 3
 - Floor will have an outline with hazard and warning tape to outline the robot's work envelope.
 -) Robot's reach = 0.8m. Outline will be 1.5m away from base.
 -) Link: [Black & Yellow Hazard Warning Tape](#)
- 2) E-Stop Test
 - Press the E-Stop while robot is in motion. Ensure it stops properly.
 -) See Video 1. Link: [Video 1 E Stop](#)
 - Press the E-Stop and attempt to start a program. Ensure it does not start.
- 3) Collaborative Function Test
 - Make a fist in front of the robot's path. Ensure that the robot stops upon contact with the person with little to no pain felt.
 -) See Video 2. Link: [Video 2 Touch Stop](#)
 -) Robot is configured at a stop force of 30N or less.
- 4) Controlled Stop Test
 - Press the red button on the control panel while the robot is in motion. Ensure the robot stops within a timely manner.
 -) This is a non-safety rated stop method. Similar to a "Pause" button.
- 5) Hard Edges
 - The control cabinet mounted to the end of the robot will be wrapped in a softening material to reduce any impacts.

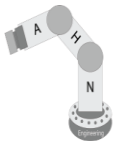
During the Demo Check List

- 1) Verbal Warning
 - Prior to a user or a group member interacting with the robot, a verbal announcement will be said to the nearby viewers.
 -) For example: "The robot is about to move, other than the person interacting with the robot, please remain outside of the hazard tape. A blue LED ring light illuminates before the robot is about to move."
- 2) E-Stop
 - A group member will hold the E-Stop pendant and monitor the user while the robot is in motion.
 -) E-Stop would be pressed upon completion of demo until next user.
- 3) Motion Indication
 - Moments before the robot is about to move, a blue LED ring light illuminates around the end effector.

Tape Link: <https://www.amazon.com/Yellow-Hazard-Warning-Safety-Equipment/dp/B06VV92GPV/>

Video 1: Link: <https://youtu.be/RGrzVLhYz9E>

Video 2: Link: <https://youtu.be/-kpckWFb7c8>

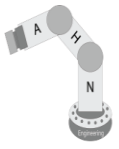


⚠ CAUTION

**COLLABORATIVE
ROBOTIC AREA**



**Robot in
motion during
demonstration.**



Appendix J: Rhodes 401 Robotic Safety Procedure

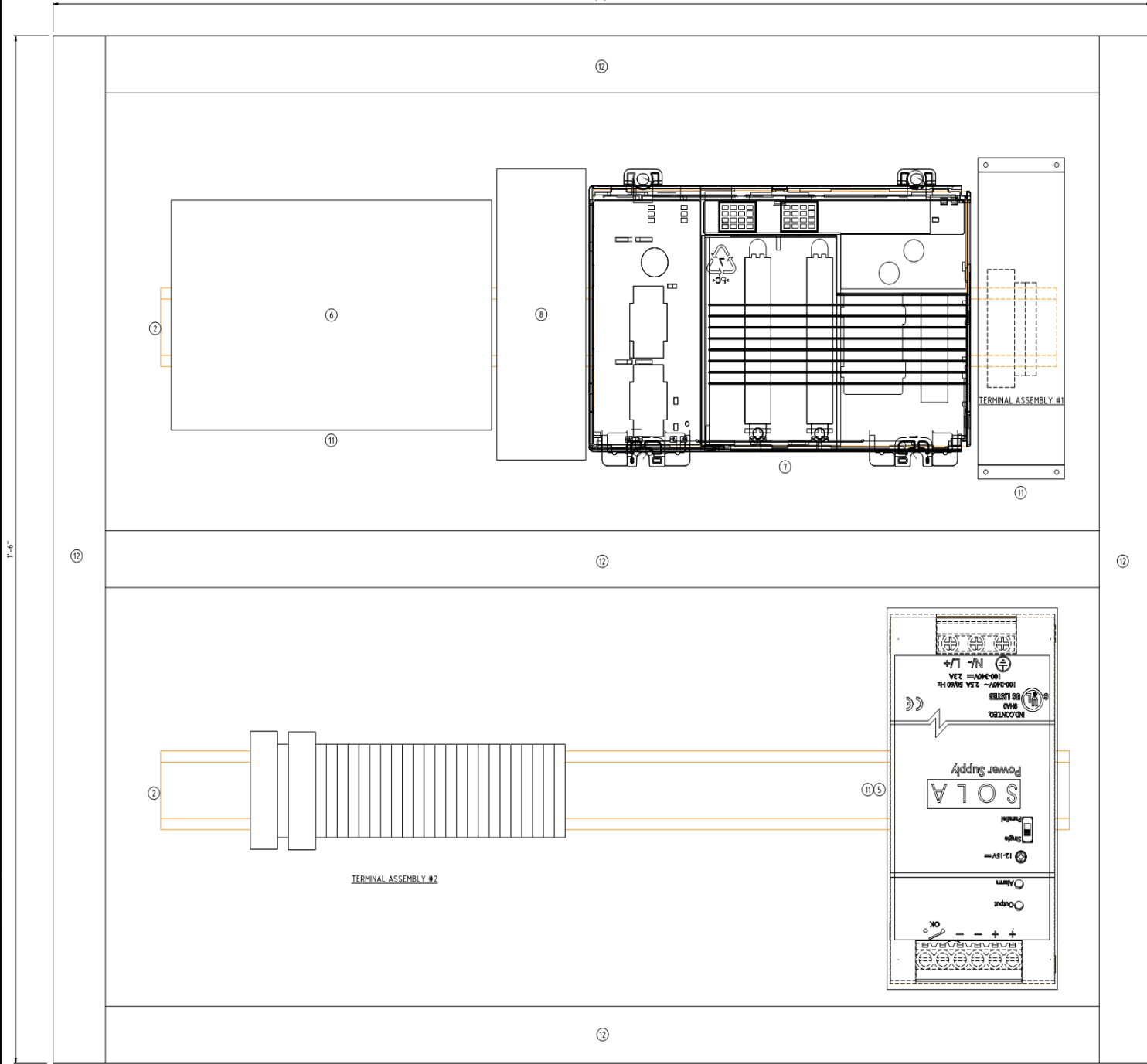
Website: <https://github.com/naterbug25/Capstone/tree/master/Report/Safety>

Appendix K: CAD Diagrams and Layouts

Website: <https://github.com/naterbug25/Capstone/tree/master/Schematics>

See next page.

1'-9"



BILL OF MATERIALS			
REF #	QTY	DESCRIPTION	MODEL #
1	1	SUBPANEL, 14"L X 20"W	-
2	AS REQ'D	DIN RAIL, 35mm X 15mm	-
3	26	FEED-THRU TERMINAL BLOCK	-
4	3	FUSE HOLDER	-
5	1	SOLA, 24V POWER SUPPLY	SDN-10-24-100P
6	1	TP-LINK, 8 PORT ETHERNET SWITCH	-
7	1	ALLEN-BRADLEY, COMPACT LOGIX PLC	1769-L23E-OB1B
8	1	ANYBUS, ETHERCAT TO IP CONVERTER	-
9	1	BUSSMAN, 10X38MM FUSE, 4A	C10G4
10	2	BUSSMAN, 10X38MM FUSE, 2A	C10G2
11	3	CUSTOM 3D PRINTED PROTECTIVE SHROUD	-
12	AS REQ'D	1" SNAP-IN WIREWAY	-

TERMINAL ASSEMBLY #1

- ④ 1 FUSE HOLDER
- ③ 2 THRU TERMINAL

TERMINAL ASSEMBLY #2

- ④ 1 FUSE HOLDER
- ③ 1 THRU TERMINAL
- ④ 1 FUSE HOLDER
- ③ 23 THRU TERMINAL

B	AS-BUILT	AJK	AJK	AJK	03/27/19
A	ISSUED FOR PROPOSAL	AJK	AJK	AJK	11/13/18
Rev	Reason	By	Chk	Appr.	Date

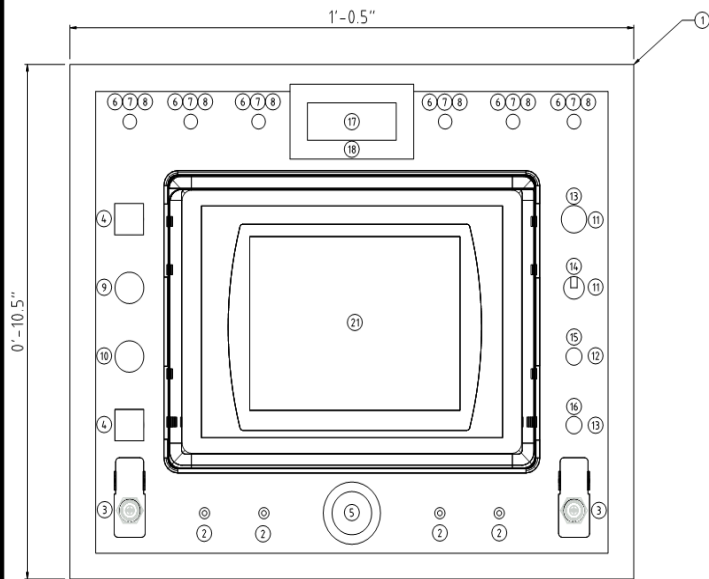
Scales NTS
Date 03/27/19 (NOT PLOTTED)
Drawn AJK
CAD Ref *minifadk*

SENIOR DESIGN
ROBOTIC FLIGHT SIMULATOR
HUBER, KUCINSKI, PALMER
CONTROL PANEL LAYOUT

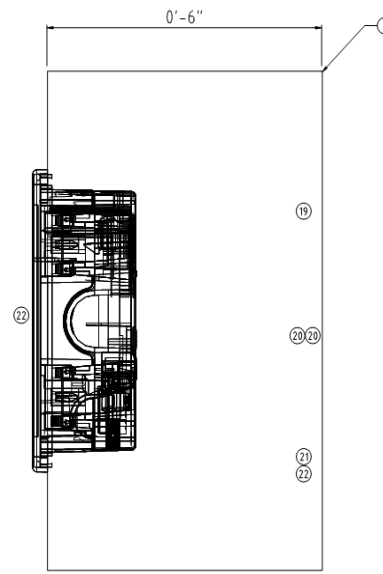
Drawing
Control Panel Active

Revision
B

SUBPANEL LAYOUT



FRONT-VIEW



SIDE-VIEW

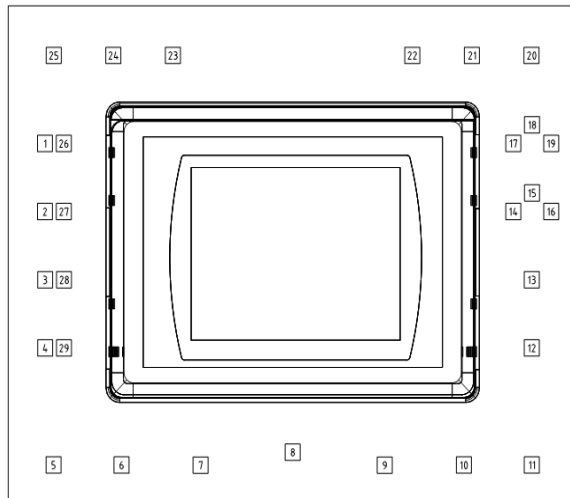
BILL OF MATERIALS			
REF #	QTY	DESCRIPTION	MODEL #
1	1	PANEL, 10.5" L X 12.5" W X 6" D	-
2	4	TAYDA ELECTRONICS, MINI TOGGLE SWITCH SPDT ON-ON	A-4567
3	2	E SUPPORT, TOGGLE SWITCHES /w GUARD	CXCP212C
4	2	UXCELL, 16mm SQUARE PUSH BUTTON, BLUE	714998124180
5	1	UXCELL, RED ILLUMINATED E-STOP PUSHBUTTON	al7031000u0114
6	6	VCC, SNAP-IN PANEL MOUNT 5mm LED LENS, CLEAR	CMC_321_CTP
7	6	VCC, 5mm LED RETAINER	RNG_268
8	6	TAYDA ELECTRONICS, 5mm LED, VARIOUS COLORS	-
9	1	ADAFRUIT, METAL PUSHBUTTON RED LED RING	559
10	1	ADAFRUIT, 16MM LED PUSH BUTTON RED LATCHING	1442
11	2	TAYDA ELECTRONICS, ROTARY SWITCH 4 POLE 3 POSITION	A-1640
12	2	TAYDA ELECTRONICS, 1K OHM LINEAR TAPER POTENTIOMETER	A-1962
13	1	TAYDA ELECTRONICS, KNURLED ALUMINUM BLACK KNOB	A-2849
14	1	TAYDA ELECTRONICS, DAVIES 1510 CLONE RED KNOB	A-389
15	1	TAYDA ELECTRONICS, DAVIES 1900H CLONE RED KNOB	A-4557
16	1	TAYDA ELECTRONICS, BLACK PLASTIC KNOB WITH WHITE POINTER	A-322
17	1	ADAFRUIT, 7-SEGMENT DISPLAY w/12C BACKPACK	B016RG90G0
18	1	TINDIE, 0.56" 4-DIGIT 7-SEGMENT DISPLAY BEZEL	-
19	1	ARDUINO NANO	UNO R3
20	2	MANUFACTURED PCBs	SX1509
21	4	THRU-TERMINAL	-
22	1	DIN RAIL	-
23	1	ALLEN-BRADLEY, C600 PANELVIEW	C600

- ①
- ②
- ③
- ④

NOTES ④

1. NOT DRAWN IN LAYOUT

I/O LAYOUT

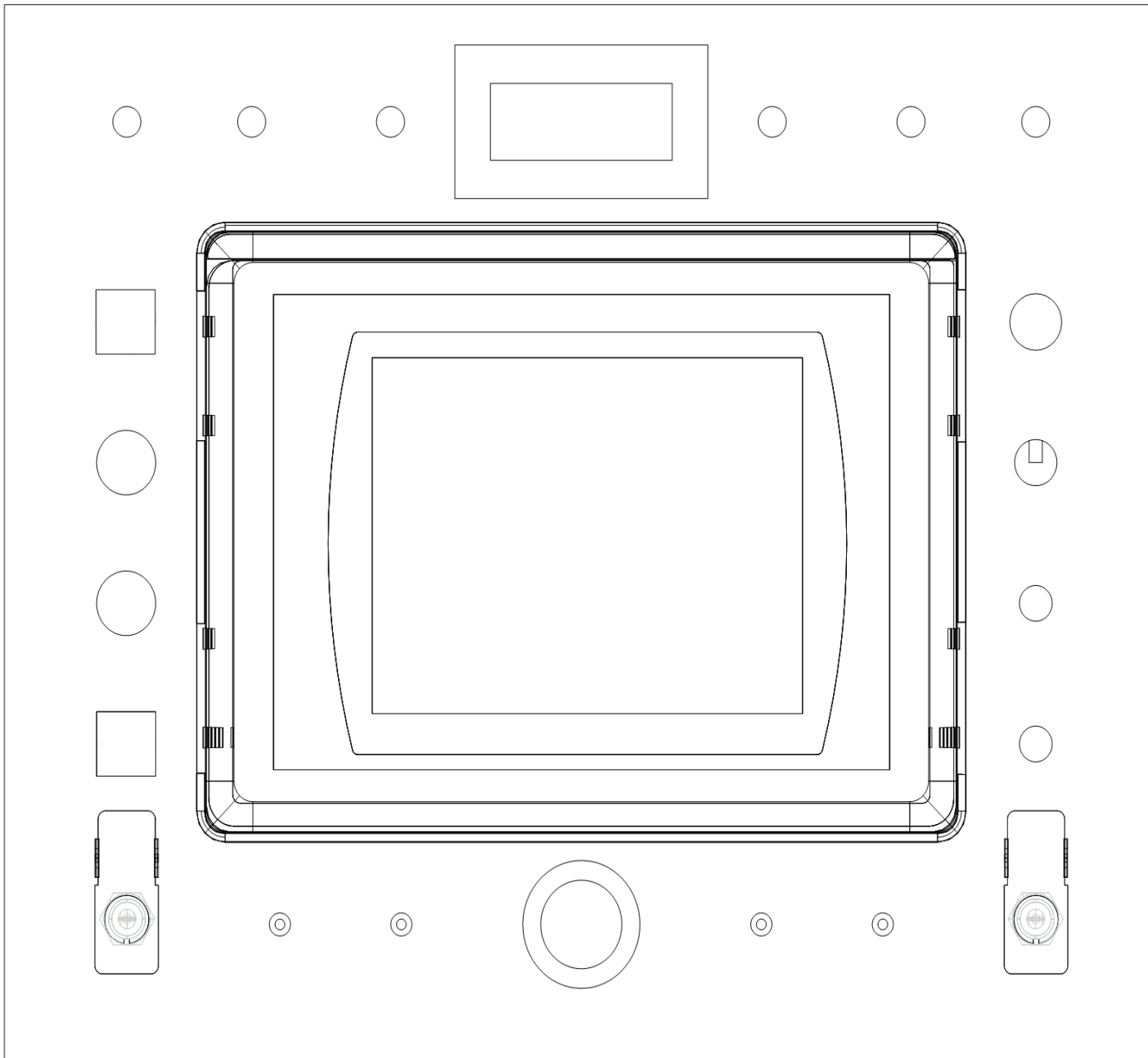


I/O SCHEDULE							
REF #	ADDRESS	I/O TYPE	COMPONENT DESC.	REF #	ADDRESS	I/O TYPE	COMPONENT DESC.
1	I_1_0	DI	PUSHBUTTON	18	I_2_6	DI	SELECTOR SWITCH POSITION 2
2	I_1_1	DI	PUSHBUTTON	19	I_2_7	DI	SELECTOR SWITCH POSITION 1
3	I_1_2	DI	LATCHING PUSHBUTTON	20	I_3_9	DO	RED LED
4	I_1_3	DI	PUSHBUTTON	21	I_3_8	DO	BLU LED
5	I_1_4	DI	TOGGLE SWITCH /w GUARD	22	I_3_7	DO	GRN LED
6	I_1_5	DI	TOGGLE SWITCH	23	I_3_6	DO	GRN LED
7	I_1_6	DI	TOGGLE SWITCH	24	I_3_5	DO	BLU LED
8	I_1_7	DI	ILLUMINATED E-STOP BUTTON	25	I_3_4	DO	RED LED
9	I_1_8	DI	TOGGLE SWITCH	26	I_3_0	DO	PUSHBUTTON LED INDICATOR
10	I_1_9	DI	TOGGLE SWITCH	27	I_3_1	DO	PUSHBUTTON LED INDICATOR
11	I_1_10	DI	TOGGLE SWITCH /w GUARD	28	I_3_2	DO	PUSHBUTTON LED INDICATOR
12	A_N_0	AI	POTENTIOMETER	29	I_3_3	DO	PUSHBUTTON LED INDICATOR
13	A_N_1	AI	POTENTIOMETER	-	-	-	-
14	I_2_2	DI	SELECTOR SWITCH POSITION 3	-	-	-	-
15	I_2_3	DI	SELECTOR SWITCH POSITION 2	-	-	-	-
16	I_2_4	DI	SELECTOR SWITCH POSITION 1	-	-	-	-
17	I_2_5	DI	SELECTOR SWITCH POSITION 3	-	-	-	-

B AS-BUILT AJK AJK AJK 03/27/18
 A ISSUED FOR PROPOSAL AJK AJK AJK 9/19/18
 Rev Reason By Chk Appr. Date
 Scales NTS Drawn AJK
 Date 03/27/18 (NOT PLOTTED) CAD Ref (B/T/ML/AL/3)

SENIOR DESIGN
 ROBOTIC FLIGHT SIMULATOR
 HUBER, KUCINSKI, PALMER
 EOAT PANEL LAYOUT

Drawing EOAT Panel Active_B
 Revision B



FRONT-VIEW

B	AS-BUILT	AJK	AJK	AJK	03/27/19
A	ISSUED FOR PROPSAL	AJK	AJK	AJK	9/19/18
Rev	Reason	By	Chk	Appr.	Date

Scales NTS
Date 03/27/19 (NOT PLOTTED)
Drawn AJK
CAD Ref BMT/afm/rev

SENIOR DESIGN
ROBOTIC FLIGHT SIMULATOR
HUBER, KUCINSKI, PALMER
EOAT PANEL FRONT VIEW

Drawing	Revision
EOAT Panel Front View	B