Rochester Institute of Technology
Department of Mechanical and Manufacturing Engineering Technology
Manufacturing and Mechanical Systems Integration

FANUC Arcmate 100iB Welding Work Cell Design

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Contents

1 Abstract

This capstone report will outline the process of designing a robotic welding work cell that will be used in Rochester Institute of Technology's (RIT) Mechanical and Manufacturing Engineering department's Foundations of Metals Lab to showcase the effects of welding on the mechanical properties of steel. This report will answer the following questions:

- What is the best way to create repeatable welds in a lab environment?
- What is the most optimal process for designing a robotic workcell?

The work cell is built in the RIT Lab 1190 and integrates the following components:

- FANUC 100iB ArcMate Robot with RJ3iB Controller
- Lincoln Electric PowerWave 455M Welder
- Allen Bradley 5380 Series Programmable Logic Controller (PLC)
- Maply Systems CMT3092X Human Machine Interface (HMI)

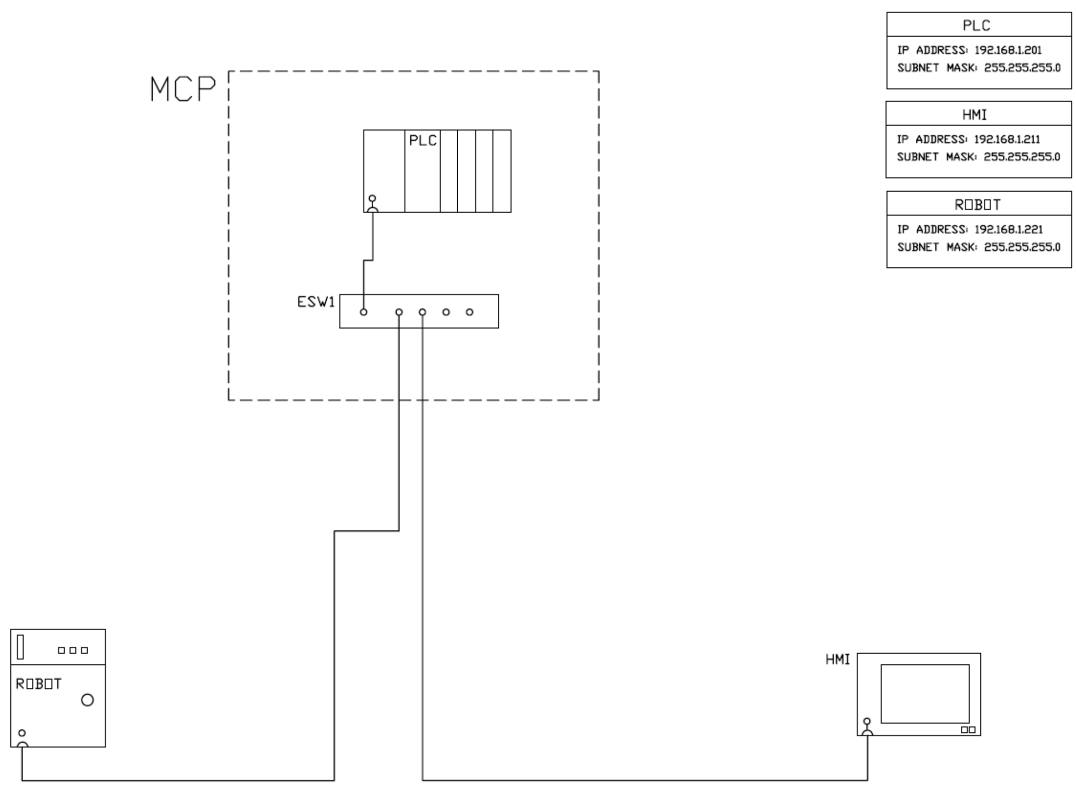


Figure 1: Network Overview

Figure 1 shows the overall network design of the system. MCP stands for Main Control Panel and ESW1 stands for Ethernet Switch 1. The cell is designed to weld tensile samples that can be tested using the MTS Tensile Tester in the RIT Lab 1190 to determine the ultimate tensile strength of the weld.

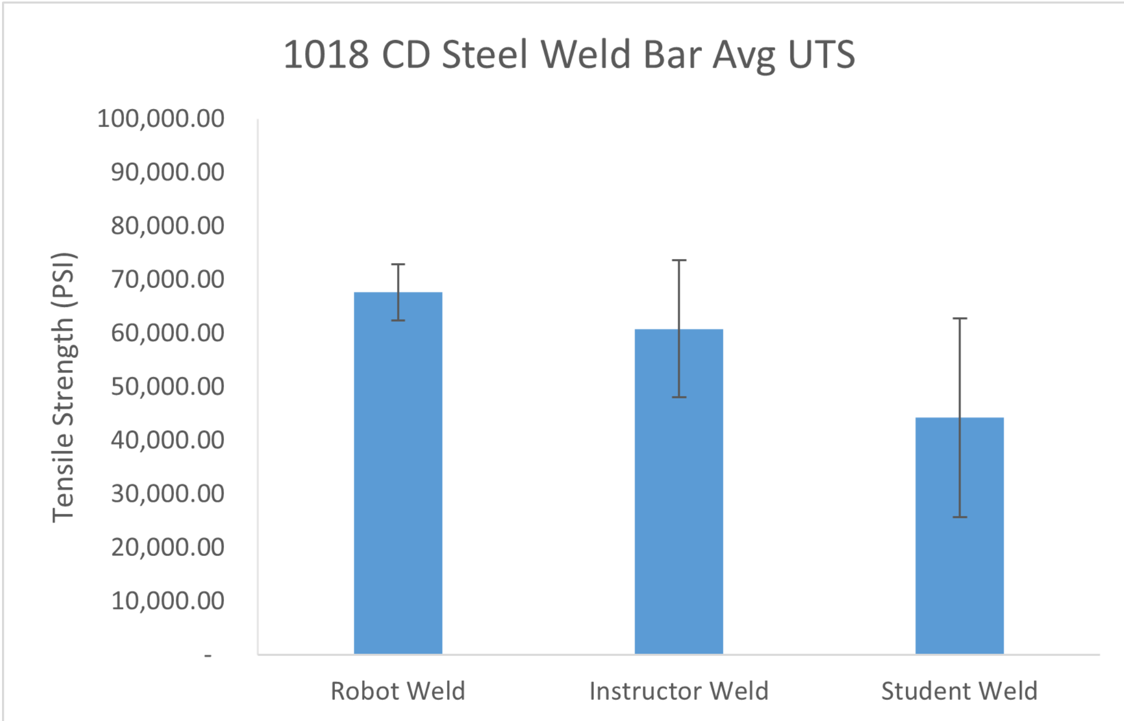


Figure 2: UTS Comparison Results Graph

Figure 2 shows the results of the welding robot in comparison to both student and instructor weld data from past semesters. The error bars seen in Figure 2 represent the standard deviation for that group. It can be seen that the robot outperformed the instructor and student weld data in both average ultimate tensile strength and repeatability.

2 Introduction

The Golisano Lab 1190 at Rochester Institute of Technology offers students many opportunities to learn with hands on labs and applications. A welding robot was purchased with the intent of adding to the classroom experience by showing a more industry standard welding application. Being in a lab environment the versatility of the cell is important while also showcasing industry standard equipment and integration. The main customer of this project is the RIT Foundations of Metals Lab where this cell will be implemented to show the differences between human and robot welds and the mechanical property changes that are caused by welding.

Throughout the report there are a variety of terms used. Below are some descriptions of terms with and visuals of the equipment used in the system.

- Programmable Logic Controller (PLC)
  - A PLC is a rugged computer that is standard in industrial automation projects. PLCs continuously monitor the states of device inputs to make decisions based on a custom program written to control the state of output devices.

- Human Machine Interface (HMI)
  - A HMI is graphical touch screen interface standard in industrial automation projects. HMIs allow the operator to view system status and also interact with the system in an easy way compared to the teach pendants available in various robot packages.

- FANUC RJ3iB Robot Controller
  - A robot controller is needed for all robots and is what executes the robot program along with coordinating the motion of all the axes of the robot. The RJ3iB robot controller is the controller manufactured by FANUC between 2001-2006.

- Lincoln Electric Power Wave 455M
  - The Power Wave 455M is a welder developed by Lincoln Electric designed for robotic welding applications. This is what generates the current needed for the welding process.

3 Purpose Statement

Traditional manual welding techniques are great for frequently changing work although, there are many cons when applied to repetitive high-volume production where consistency is the priority. Similar to other robotic applications, welding is no different in that highly repetitive tasks may be automated to speed up production and increase quality with the use of a robot.

The purpose of this project is to develop an automated welding work cell to weld tensile samples for the MCET Foundations of Metals Class. The welded tensile samples are used to demonstrate the effect of welding on the mechanical properties of steel. Currently, students are welding the samples manually creating poor results and causing difficulties seeing the true effects of welding on the mechanical properties of the material. This project will also serve as a lab improvement and allow for a variety of designed experiments to test the effects of certain welding parameters on the mechanical properties of the material.

The project also showcases the development phases that go into the design of a production machine or system along with the integration of industry standard equipment into a functional work cell. The system was designed to be adaptable to various welding tasks that could take place in a lab environment while still focusing on Foundations of Metals Class as the main customer.

4 Literature Review

4.1 Focus on Robot Application

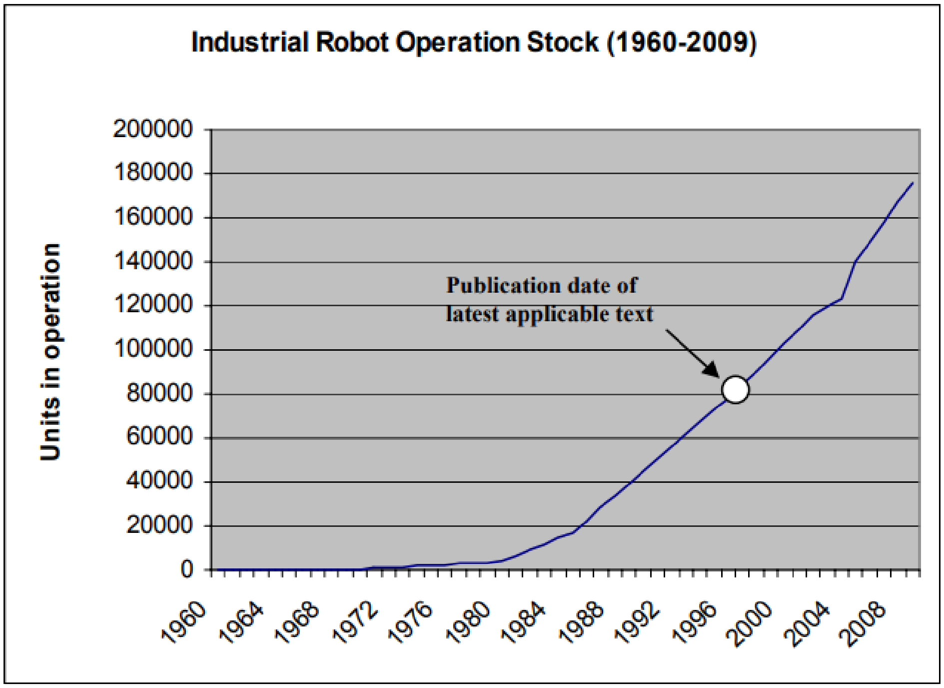


Figure 3: Industrial Robot Operational Stock 1960-2009 [13]

Since the introduction of industrial robots in the 1960's, the industrial robotics industry has grown consistently at an increasing rate. Figure 3 helps to illustrate the rapid increase in operational robots since 1960. Previously individuals that studied robotics likely focused on the actual design and control system behind many of the robots we see today. Although with the increase in production of the industrial robots and increasing demand in manufacturing facilities, individuals who study robotics will likely be more focused on robotic system/work-cell design and the application of these robots rather than the robot design.

4.2 Work Cell Design for Lab Environment

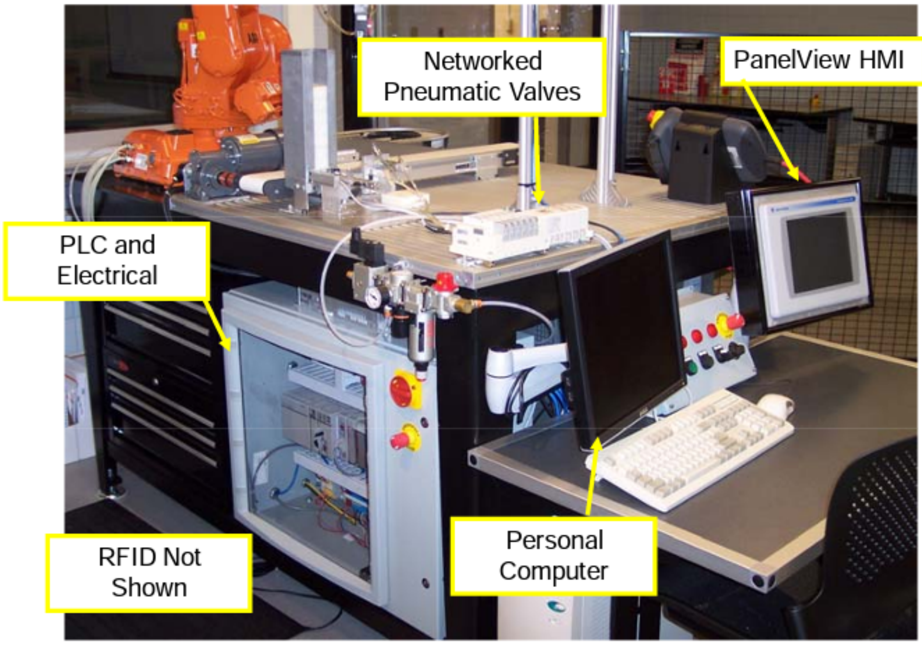


Figure 4: Example of Work Cell Designed for Lab Environment [7]

Figure 4 shows the implementation of a robotic work cell in and educational environment. While lower cost alternatives to name brand robots are available, they don't allow students to have hands on experience with industry standard hardware and software. Devine points out in this article the major advancements of offline programming and simulation environments are now available with these industrial robots. They not only allow for the programming of the robots prior to receiving the hardware but also letting dozens of students learn when only one physical robot is available, very common in educational settings. Offline programming also allows for much of the troubleshooting phase to be completed before even touching the robot. This can reduce the startup time of a system drastically.

Devine also points out the advantages of using industrial networks in place of discrete I/O in educational settings. Having a single network cable compared to multitudes of discrete wires not only makes initial integration difficult but also eliminates the major deterrent preventing change to the work cell. In a lab environment, courses are consistently changing and adapting with the times meaning an agile work cell is a priority in an educational environment.

4.3 High Performance HMI Graphics

Prior to HMIs (Human Machine Interface), control walls or other monitoring systems consisted of multiple instruments (mostly pneumatic) which were logically grouped based on the system. Readings were displayed using paper strip charts and any alarms were displayed using separate annunciator panels. These systems had the advantage of allowing a large overview of the system for the operators but also caused the addition of new instruments to be very expensive. This led to many of the control walls to become outdated over time based on system changes. [9]

Current HMIs solved many of the previous issues by replacing the physical instruments with software displays allowing the displays to be reconfigured easily. Current HMIs also brought their own problems as well, with the smaller screen size the once large overview is substantially reduced and instead alarms are used to alert the operator of any issues outside their view. With the amount of data available to modern systems, large amounts of data are displayed but little information. Information can be defined as data in context made useful. Graphics produced on these displays are also based on flashy graphics examples causing very poor usability. [9]

The HMI is the operators window into the process and is a critical element for the effectiveness of the operation. Some of the main principles discussed in the book are as follows:

- Clarity and simplicity are essential to HMI design.
- The intentional use of color to enhance situational awareness. For example, red should only be used for fault conditions or alarms.
- The use of an overview screen for a system and the importance of being able to navigate to any system screen from this overview.

5 Research Question

The research questions that will be addressed include:

- What is the best way to create repeatable welds in a lab environment?
- What is the most optimal process for designing a robotic workcell?

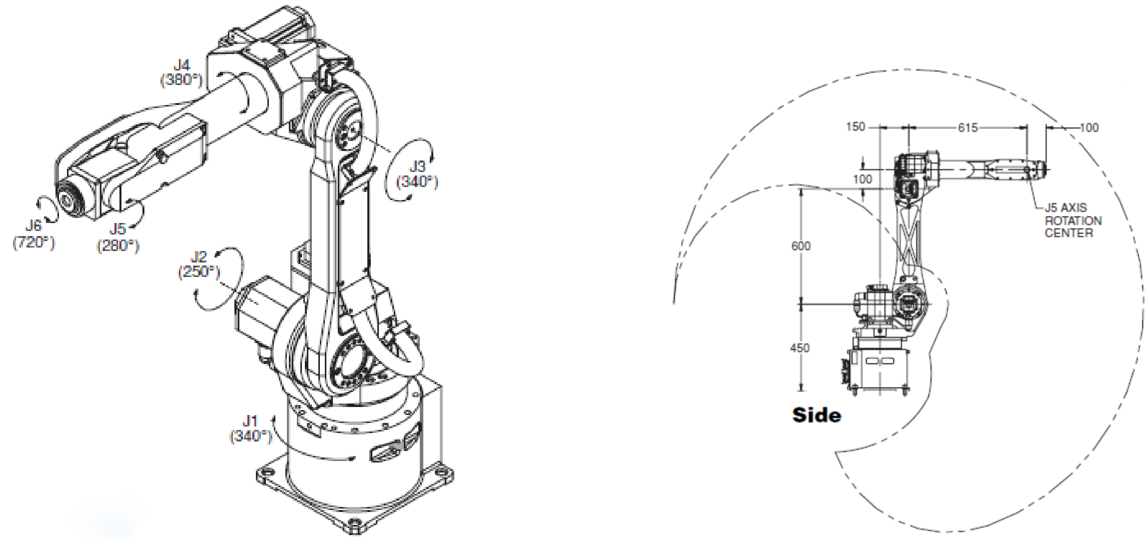
Design Phases

6 Mechanical Design

The first step of the machine design process includes the mechanical design and layout of the work cell. This includes the welding fixture design, sensor selection, and guarding / safety decisions.

6.1 Robot Details

In this system a FANUC 100iB Arc-Mate robot is used with a Lincoln Electric PowerWave 455M welder. The 100iB Arc-Mate robot is a 6 axis robot with a 6kg payload capacity. The robot has a 1373mm reach and a repeatability of +- .08mm.



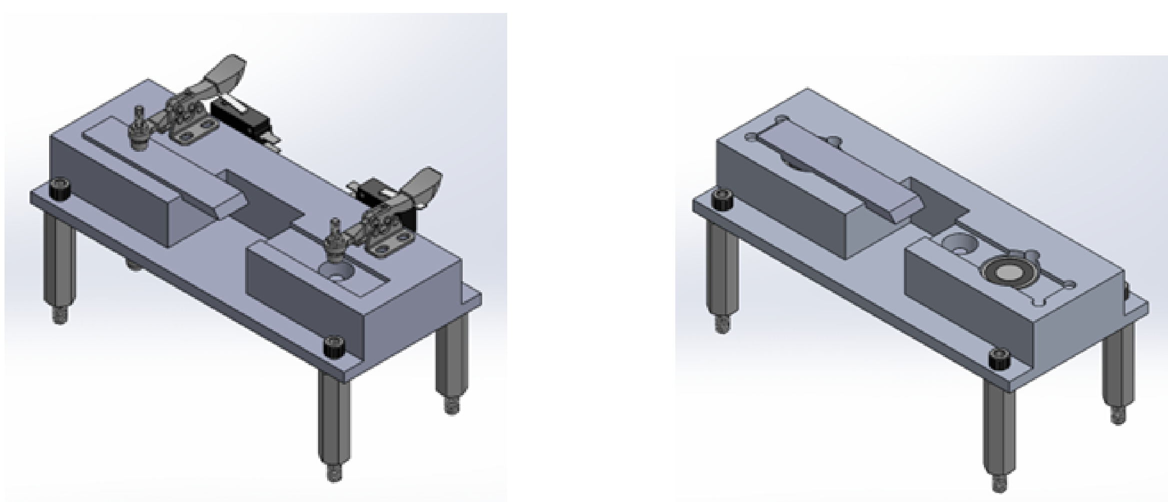
(a) FANUC 100iB Iso View (b) FANUC 100iB Working Envelope

Figure 5: FANUC 100iB Technical Images

6.2 Welding Fixture Design

The key design attributes that needed to be solved through the fixture design included:

- Capable of centering tensile samples that vary in length.
- Ability to clamp tensile samples in place during the weld.
- Capable of grounding the tensile samples.
- Include sensor to detect tensile sample presence.
- Include method of verifying tensile samples are clamped.



(a) Toggle Clamp Design (b) Electro-Magnet Design

Figure 6: Fixture Design Comparison

The two original designs developed can be seen above in figure 6. The designs include different methods of clamping while the other features were very similar. The first design uses toggle clamps to clamp the samples and limit switches to verify the samples are clamped (6a). The second design utilizes electro-magnets to clamp the specimen and relies on the control output to the magnets to verify the samples are clamped (6b). Both designs use inductive proximity sensors to sense the presence of the tensile samples. Both designs also use an external laser to mark the robots taught weld points. This is used to center the samples no matter the variation in sample length. Both designs are designed with 6061 aluminum due to its non-magnetic properties and electrical conductivity for grounding.

		Toggle Clamp Design		Electromagnet Design	
Criteria	Weight	Rank	Weighted Score	Rank	Weighted Score
Manufacturability	2	0.5	1	0.5	1
Assembly	2	1	2	0.5	1
Reliability	3	1	3	0.75	2.25
Part Count	1	0.5	0.5	0.75	0.75
Effect on Welding Path	3	0.25	0.75	1	3
Simplicity	2	0.5	1	1	2
			8.25		10

Ranking	
1	Best
0.75	
0.5	Average
0.25	
0	Worst

Figure 7: Welding fixture design decision matrix

Figure 7 above shows the decision matrix used to determine the best fixture solution based on a set of criteria and weighting factors. The electro-magnet design (figure 6b) was decided as the best solution primarily based on its minimal effect on the welding path of the robot along with eliminating the need for limit switches.

6.3 Safety and Guarding

Because this work cell is being implemented in a lab environment where floor layouts are consistently changing and floor space is limited, it was decided that temporary welding curtains will be used when the cell is in operation. Omron light curtains are utilized protect the work area where the tensile samples are changed between welds. These light curtains will fault the robot if the beam is broken.

6.4 Overall Cell Layout

The physical location of the robot, welding table, robot controller, and welding power supply were chosen based on optimal traffic flow through the lab.

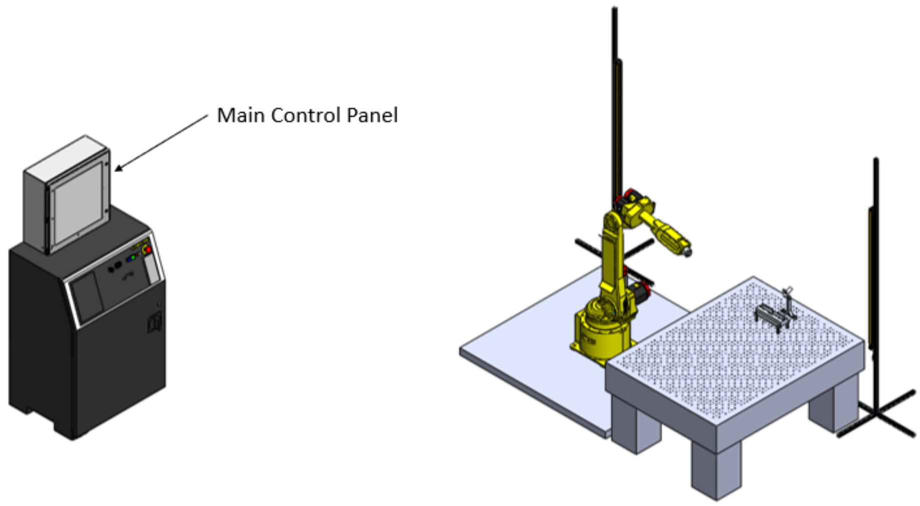
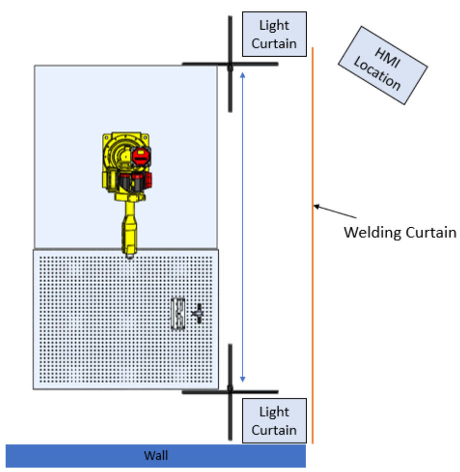
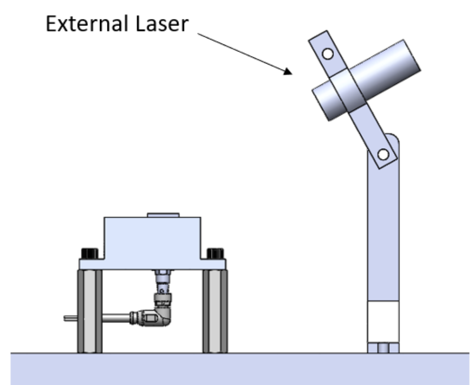


Figure 8: Iso-View Layout of Work Cell

Figure 8 shows the location of main control panel which is mounted on top of the RJ3iB robot controller along with the locations of light curtains and welding fixtures. The welding power supply is located directly to the right of the robot controller (not shown in CAD).



(a) Top View Cell Layout



(b) Fixture Side View with Laser

Figure 9: Work Cell Layout

Figure 9a shows the top-view of the work cell including the HMI location. The HMI is mounted in a podium on wheels allowing it to be moved as needed. Also shown is a mobile welding curtain separating the HMI operator from the weld. Figure 9b shows how the fixture is mounted to the welding table along with the mounting of the external laser used for centering the samples. The fixture is elevated allowing for the proximity sensor cables to enter through the bottom of the fixture. The laser will project a line connecting the weld start and weld end points (taught robot positions) allowing the operator to center the tensile samples accurately in relation to the robots welding path.

7 Electrical/Hardware Design

7.1 Load Calculations

Prior to completing the electrical schematics, it is important to perform load calculations of the system to determine what device ratings will be needed.

Three power supplies are used in this system. One will be used only to power the PLC Mod and SA power, the second will be used to power the remaining 24VDC devices, and the third will be used to power the 5VDC external laser. To determine the rating of the power supplies required, it is necessary to compile the current ratings of each device to ensure the total current draw of all devices on each power supply does not exceed the power supply's rating. The following tables display the current ratings of each device:

Table 1: Power Supply 1 (PWS1) Device Current Ratings

Power Supply 1	
Device	Current Draw (A)
Electromagnet (2)	0.12 [11]
Proximity Sensor (2)	0.20 [8]
Ethernet Switch	0.20 [3]
HMI	1.00 [14]
Light Curtain Emitter	0.30 [12]
Light Curtain Receiver	0.30 [12]
Total	2.12

Table 2: Power Supply 2 (PWS2) Device Current Ratings

Power Supply 2	
Device	Current Draw (A)
PLC MOD Power	0.475 [2]
PLC SA Power	0.010 [2]
Total	0.485

Table 3: Power Supply 3 (PWS3) Device Current Ratings

Power Supply 3	
Device	Current Draw (A)
Laser	0.02 [1]
Total	0.02

Using Tables 1-3 to understand the minimum required rating of each power supply, the following power supplies were selected based on product availability:

Table 4: Selected Power Supplies

Selected Power Supplies		
Device	Rating	Part Number
PWS1	5A	Wago (787-722)
PWS2	3.75A	PSM24-090S
PWS3	1.5A	PSL-05-010

Based on the maximum current ratings of the selected power supplies, the panel main circuit breaker rating can be specified. In this case a 10A circuit breaker was selected.

7.2 Electrical Schematics

AutoCAD Electrical was utilized to complete the electrical schematics for the system. The objective of electrical schematics are to not only guide in the wiring of the control panel but also as a troubleshooting reference for later in the systems life. The wire labels used correspond to line numbers in the schematic package for easy reference. The full schematic package can be see in Appendix A.

The following electrical components were supplied by RIT for the project:

- Allen Bradley Compact Logix PLC (5069-L306ER)
- Allen Bradley Digital Input Card (5069-IB16F)
- Allen Bradley Digital Output Card (5069-IB16F)
- Allen Bradley Ethernet Switch (1783-LMS5)

The electrical schematics were designed based on the supplied components, power supplies (Table 4), and fuses (Table 8). The remaining electrical components needed were sourced from Automation Direct and Allied Electronics based on availability and lead times. Control relays were used for all PLC outputs of the system to ensure the current load of the PLC output card is not exceeded.

7.2.1 Fuse Calculations

Fast acting fuses are used to protect the power supplies in the system from any short circuit or overload conditions. Each of the 24V power supplies will wire directly to a fuse prior to powering each of the devices. Isolating devices on separate fuses can also be beneficial when powering up the system so that each device group can be powered on one at a time rather than all at once. This system will use 3 fuses to power the 24V devices. The following tables depict which devices are powered by which fuse:

Table 5: Fuse 1 Device Current Ratings

Fuse 1	
Device	Current Draw (A)
Ethernet Switch	0.20 [3]
HMI	1.00 [14]
Total	1.20

Table 6: Fuse 2 Device Current Ratings

Fuse 2	
Device	Current Draw (A)
Electromagnet (2)	0.12 [11]
Proximity Sensor (2)	0.20 [8]
Light Curtain Emitter	0.30 [12]
Light Curtain Receiver	0.30 [12]
Total	0.92

Table 7: Fuse 3 Device Current Ratings

Fuse 3	
Device	Current Draw (A)
PLC MOD Power	0.475 [2]
PLC SA Power	0.010 [2]
Total	0.485

Based on Tables 5-7 the selected fuse ratings can be seen below in Table 8.

Table 8: Fuse Ratings

Fuse Ratings	
Fuse	Current Rating (A)
F1	2
F2	3
F3	2

7.2.2 Wire Gauge and Color

The next step is to determine the wire color and gauge needed for each device. Table 9 below shows the color associated with each voltage. 18AWG wire was used for all devices in the panel due to availability and ease of wiring. Figure 10 from the UL508 Standard shows the 18AWG wire can handle up to 7A which is sufficient for the current device loads.

Table 38.1
Ampacities of control circuit conductors

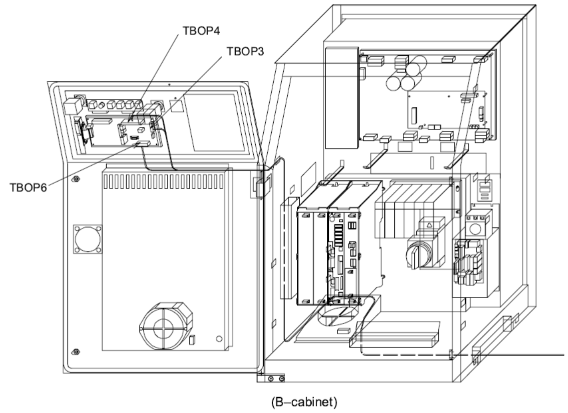
Ampacity, amperes	Conductor size	
	AWG	(mm^2)
10	16	(1.3)
7	18	(0.82)

Figure 10: UL508 Table for Wire Gauge Ratings [10]

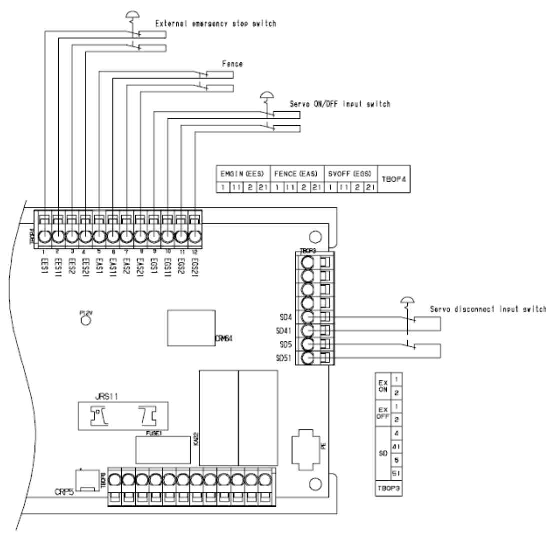
Table 9: Wire Colors

Wire Color	
Color	Voltage
Blue	24VDC
Blue/White	0VDC
Red	120VAC
White	AC Neutral
Green/Yellow	Ground

7.2.3 External Emergency Stop Wiring



(a) RJ3iB Cabinet Wiring



(b) RJ3iB E-Stop Wiring Terminals Pinout

Figure 11: RJ3iB External E-Stop Wiring [6]

Figure 11 shows the Fanuc RJ3iB robot controller schematics used to determine the proper location for the external E-Stop to terminate. This will allow an external emergency stop to be located at the HMI podium that will function the same as the emergency stops located on the teach pendant and on the controller.

7.2.4 Light Curtain Wiring

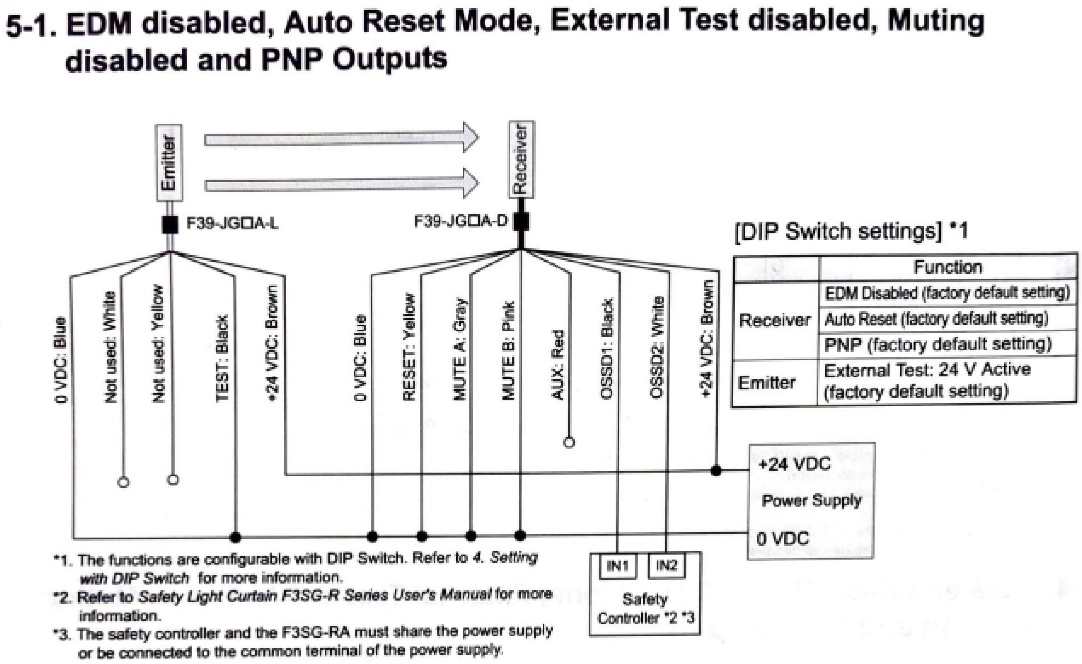


Figure 12: Light Curtain Schematic [12]

Figure 12 shows the wiring schematic of the Omron light curtains used to design the schematics. Due to the lack of availability of a safety controller, the PLC was used in its place to fault the robot when the light curtain is broken using software. In an industrial application this would not be a suitable replacement for the safety controller.

7.2.5 Proximity Sensor Wiring

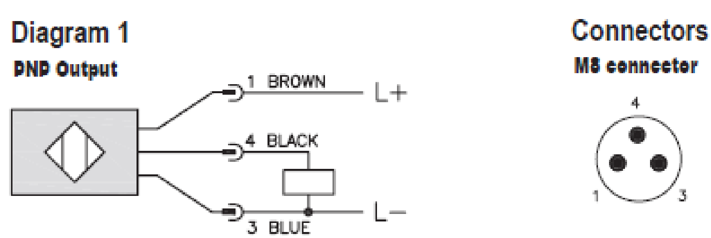


Figure 13: Proximity Sensor Schematic [8]

Figure 13 shows the wiring schematic for the inductive proximity sensors interfacing with the system. The figure also shows the pinout of the M8 cable connector. The black wire seen in the schematic is used as the N.O. output connecting to the PLC input card.

7.3 Control Panel Design

A control panel is a clean and efficient way to house the electrical components needed in a system. Components can be DIN mounted on a subpanel which allows for easy access and wiring.

SolidWorks was utilized to design the subpanel layout and select the enclosure size needed for the system. By creating a 3D assembly of devices the required subpanel and enclosure dimensions become apparent.

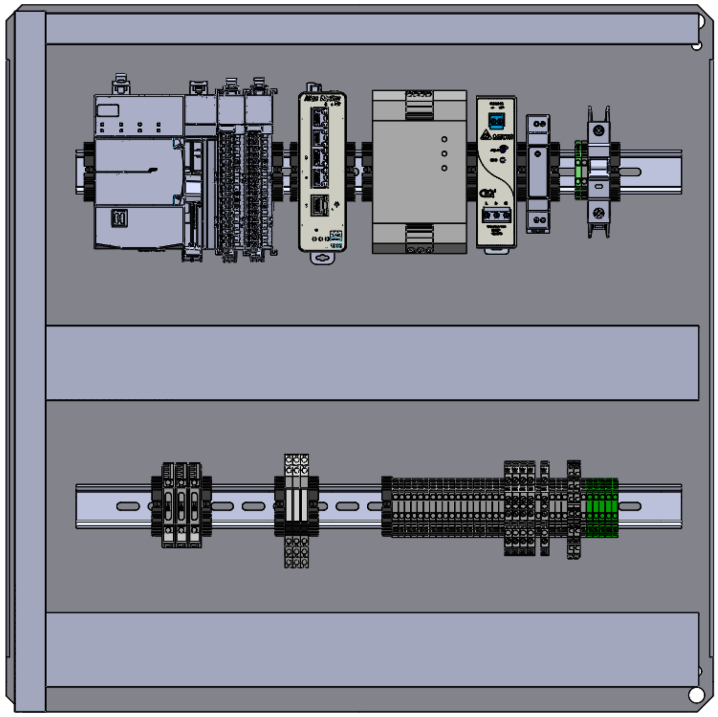
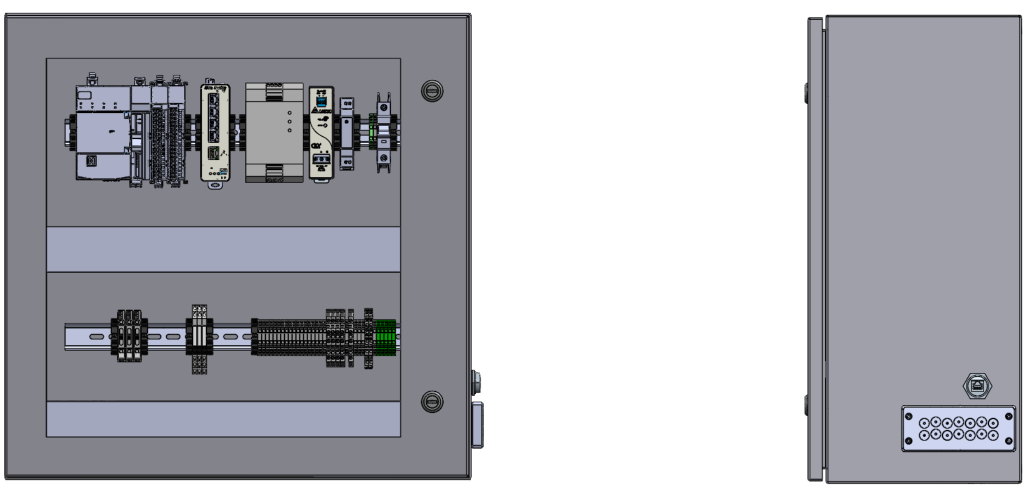


Figure 14: SolidWorks Subpanel Model

Figure 14 shows the design of the sub panel using SolidWorks. Majority of the device models were available to downloaded from Automation Direct. It is important to maintain at least a 1in space between the tops and bottoms of the DIN mounted devices and the wire duct. This ensures there will be enough space to wire the devices properly. This also ensures there will be enough space for air movement in the panel for device cooling.



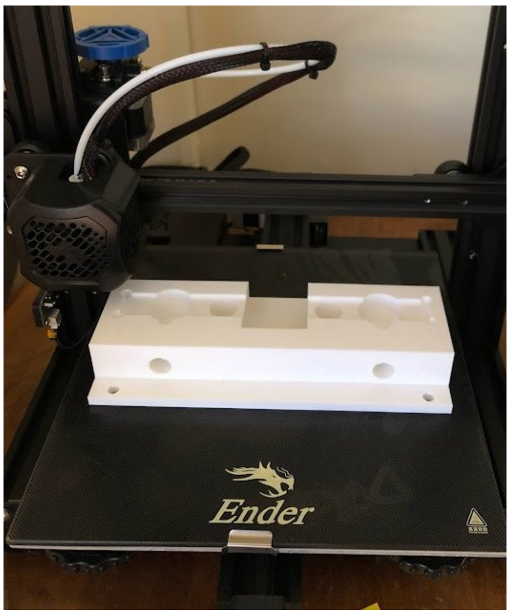
(a) SolidWorks Enclosure Front View

(b) SolidWorks Enclosure Side View

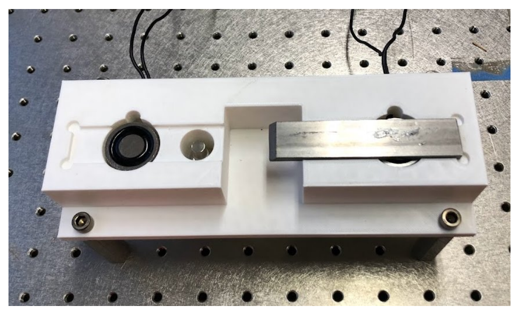
Figure 15: SolidWorks Enclosure Model

Figure 15 shows the Wiegmann Ultimate Series enclosure selected which is a 24x24x10in steel enclosure with a polycarbonate window. The window allows the design of the sub panel to be displayed in the lab environment. Figure 15b shows the side view of the enclosure which includes an IP65 nylon cable entry plate with (14) 5-11mm openings. This provides an easy way to organize the field wiring when there are multiple cables entering the enclosure. Also seen in Figure 15b is an RJ45 bulkhead used for easy connection of the HMI or PC to the system network. The Bill of materials for all components used in the system can be found in Figure 67 in Appendix B.

8 Mechanical Build



(a) 3D Printed Fixture

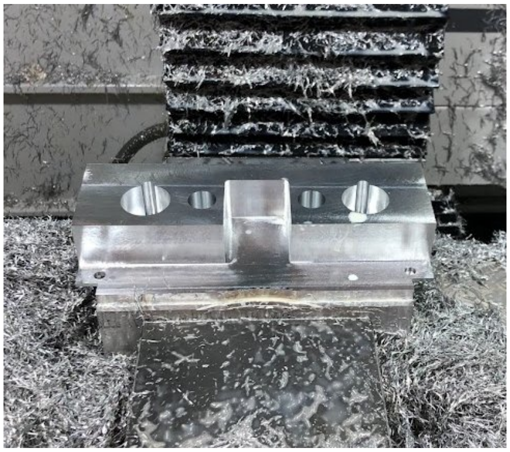


(b) 3D Printed Fixture Clearance Test

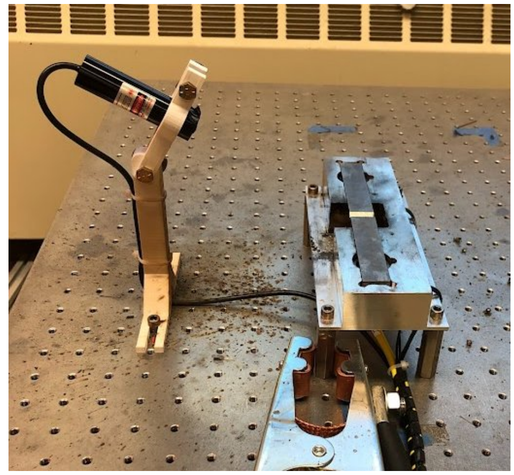
Figure 16: 3D Printed Fixture

A 3D printed version of fixture, seen in Figure 16 was used to test clearances of the proximity sensors and electromagnets. The fixture was printed on an Ender 3 V2 printer.

When clearances were finalized, Auto-desk Fusion 360 was used to develop the tooling paths and G-code for machining the fixture from 6061 aluminum. A Tormach 1100 was used to machine the fixture in the RIT Lab 1190.



(a) Machined Fixture



(b) Fixture Mounted in Cell

Figure 17: Fixture Manufacturing and Mounting

Figure 17a shows the fixture after machining in the Tormach 1100. Figure 17b shows the fixture mounted in the cell. The 3D printed laser mount can also be seen in this figure.

(a) Podium Cutout

(b) Finished Podium

Figure 18: Podium Build Process

Figure 18 shows the process of building the podium to fit both an HMI and E-stop. Based on the spec sheet of the HMI, a jig saw was used to cut the mounting hole. Due to the thickness of the podium (compared to typical metal enclosures), the E-stop push button was not able to be mounted directly to the wood. Instead a 3D printed bracket was used to mount the E-stop to the podium.

9 Electrical Build

Using the Solidworks models seen in Section 7.3, drawings were created to guide the building of the control panel.

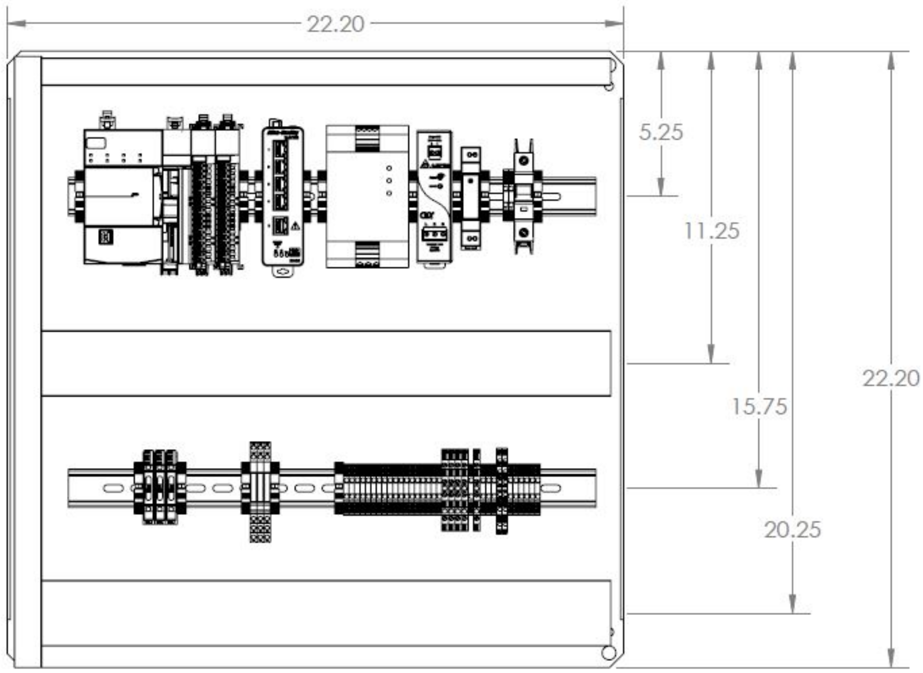
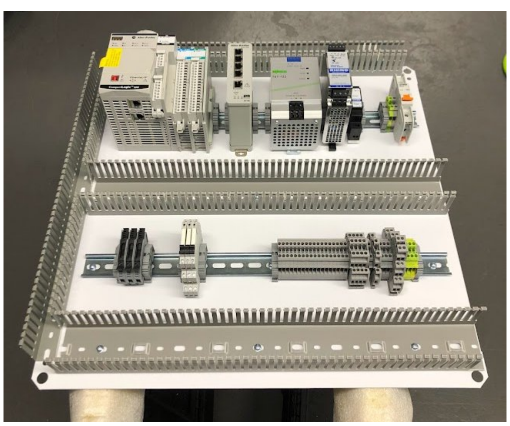
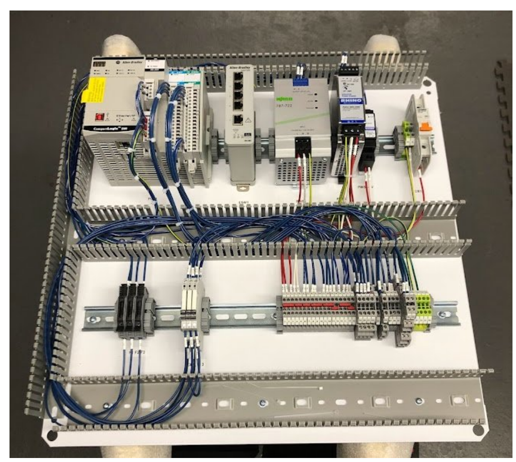


Figure 19: Sub-panel Shop Drawing

Figure 19 shows the drawing used to build and assemble the sub-panel of the control panel. 8-32 x 3/8" screws were used for the mounting of both the din rail and wire duct.



(a) Sub-panel Hardware Layout



(b) Wired Sub-panel

Figure 20: Sub-panel Wiring

Figure 20 shows the wiring process of the sub-panel.

Figure 21: Final Wiring of Control Panel

Figure 21 shows the sub-panel mounted within the enclosure.

Figure 22: Control Panel Mounting and Field Wiring

Figure 22 shows the mounting of the control panel on the RJ3iB robot controller along with the field wiring routing from the enclosure.

(a) HMI Wiring on Podium

(b) Podium Wiring

Figure 23: Wiring of HMI in Podium

Figure 23 shows the wiring of the HMI and E-stop and how the wiring was routed in the podium. The podium was designed so that it can be fully disconnected from the cell if something in the lab needs to move. This was done using electrical quick disconnect crimps to connect the cables from the enclosure to the cables from the podium.

10 Software Design

Based on the mechanical design, the system's inputs and outputs can be listed to allow for proper hardware selection:

Table 10: System Inputs and Outputs

Inputs	**Outputs**
Inductive Proximity Sensor (2)	DC Electromagnet (2)
Light Curtain	DC Laser
Emergency Stop	

10.1 Network Design

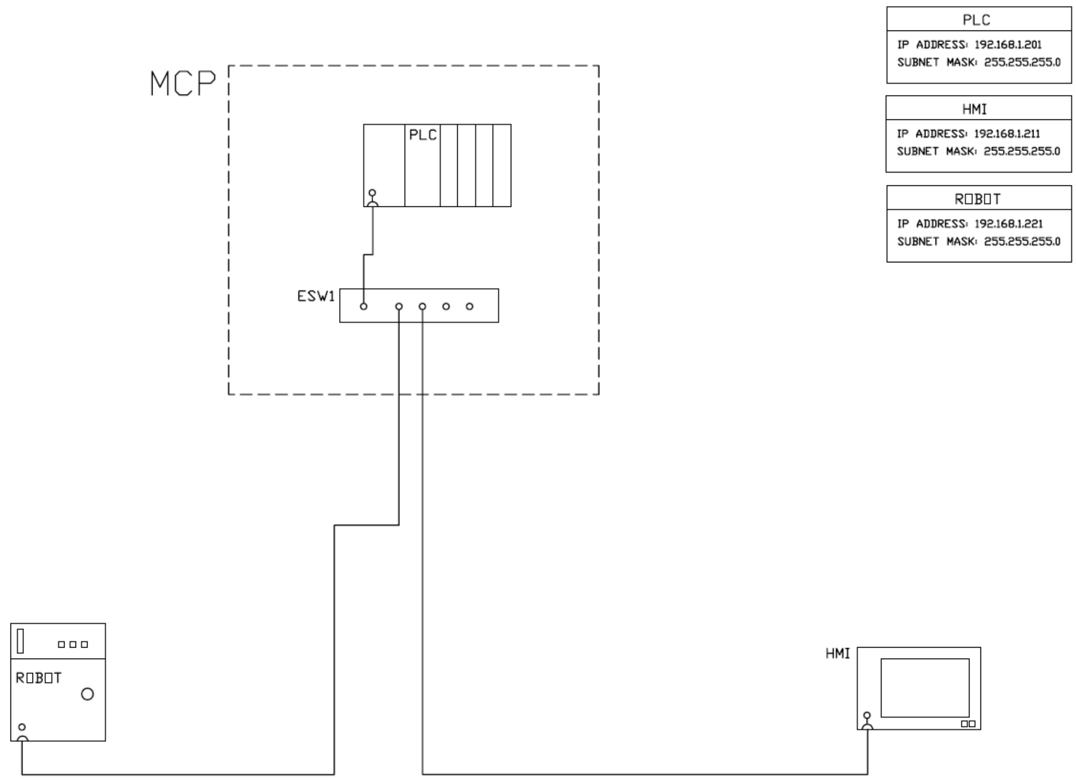


Figure 24: Network Overview

Figure 24 shows how each device on the system is connected on the network. The system will utilize the Ethernet I/P Protocol to communicate between devices. The PLC will act as the central brain of the system and communicate to both the robot and HMI. The class C address space was used with the network portion of the address being "192.168.1" with the host portion of the address (last octet) being unique between all devices. The default subnet mask of 255.255.255.0 was used as well. Setting up a local network like this allows only devices with the same network address (192.168.1) to communicate, meaning send packets of data back and forth. This is a convenient way to isolate sets of devices when on a much larger network as well.

10.2 Robot Design

The robot in this system will be used as an actuator controlled by the PLC. This allows the PLC to act as the brain of the system and the robot will simply provide status and position feedback to the PLC. There are multiple setup procedures required for the robot to be controlled remotely by a PLC.

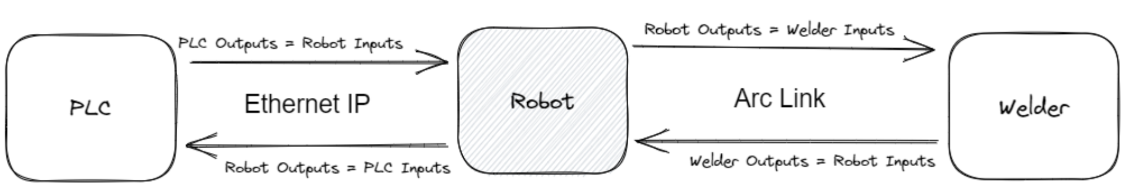


Figure 25: Robot Communication Overview

Figure 25 shows the devices that the robot is communicating with in the system. The robot is communicating with the welder via Arc Link and the PLC via Ethernet IP. The diagram also helps to point out that from the robots perspective any PLC outputs are seen as robot inputs and vise versa.

10.2.1 Robot Upgrades

Prior to this project, the robot was in an unusable state and a variety of upgrades needed to be accomplished prior to starting the cell design. The following list includes the options and parts purchased:

- Assign a New F Number
  - The F Number of a Fanuc robot is the identification number of the robot, without it technical support cannot access any information about the robot. Since this robot was a used robot the controller and robot did not match, therefore a new F Number needed to be assigned based on serial numbers found on the robot and controller.
- Software Re-license and Ethernet IP Adapter
  - The robot controller did not have Ethernet IP communication capabilities when purchased. The Ethernet Adapter is a purchased software option that is required to send data over Ethernet IP. Fanuc also required a software re-license to be purchased for the new F Number that was being assigned to the robot.
- Wire Reel and Polymer Conduit
  - The wire reel is used to hold the welding wire and allow the robot wire feeder to pull the wire from it. The conduit is what connects the robot wire feeder to the wire reel for the wire to travel through.
- Ground Cable and Power Cable
  - The ground cable is connected to the negative stud of the Power Wave 455M and is needed to complete the circuit from the welder output. The power cable is connected to the positive stud of the welder and is needed to carry the current of the welder to the wire feeding from the robot.

10.2.2 System Configuration Setup

The system configuration menu on a Fanuc robot is very important to ensure the system will operate correctly. In this system the robot needs to be controlled by an external device (PLC) and use its UOP input signals to control its actions. The system is also configured to use select digital output signals based on the state of the robot as feedback to the external device in control. To navigate to this screen on the teach pendant use the following instructions:

- Menu → System → Type (F1) → CONFIG

A table of values that need to be set in the system configuration menu to run the robot remotely in auto mode can be seen below in Figure 26.

System Configuration Menu		
Item	Description	Value
1	Use Hot Start:	FALSE
2	I/O Power Recovery:	RECOVER ALL
3	Cold Start Autoexec program:	MAIN
4	Hot Start Autoexec program:	MAIN
5	Hot Start done signal:	DO[0]
6	Restore selected program:	FALSE
7	Enable UI Signals:	TRUE
8	START for CONTINUE only:	TRUE
9	CSTOPI For ABORT:	TRUE
10	ABORT All Programs By CSTOPI:	TRUE
11	PROD_START depend on PNSTAROBE:	FALSE
12	detect FAULT_RESET signal:	RISE
13	Use PPABN Signal:	GROUP 1: FALSE
31	Signal To Set In Auto Mode:	DO[20]
32	Signal To Set In T1 Mode:	DO[21]
33	Signal To Set In T2 Mode:	DO[22]
34	Signal To Set If Estop:	DO[23]
35	Set if INPUT SIMULATED:	DO[24]
36	Set if OUTPUT SIMULATED:	DO[25]
44	Hand Broken:	GROUP 1: DISABLE
45	Remote/Local Setup:	Remote
47	UOP Auto Assignment:	Simple(CRMA16)

Figure 26: Robot System Config Menu for Remote Operation

10.2.3 Robot Tool Frame Setup

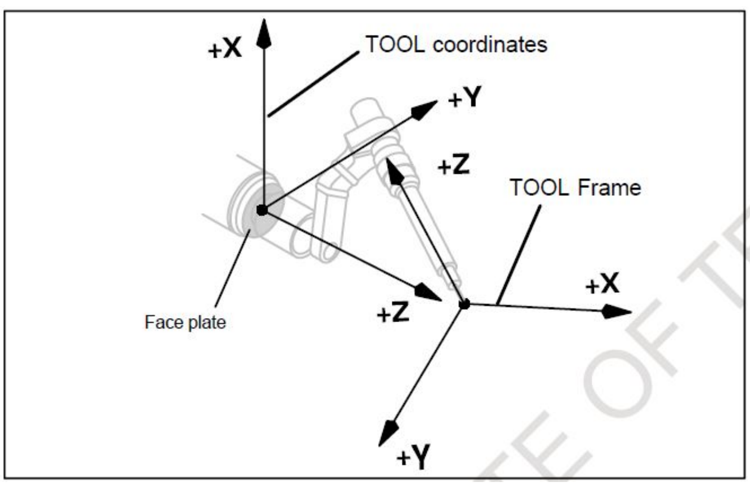
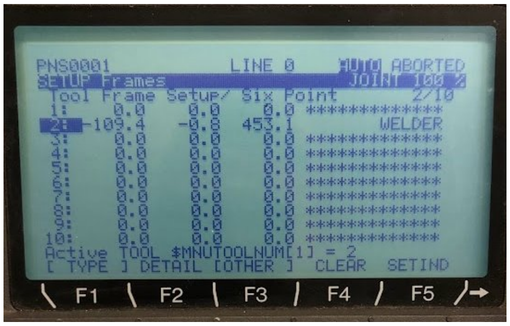


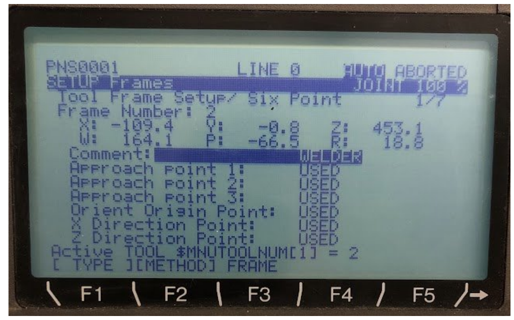
Figure 27: Image of Tool Frame [4]

Figure 27 shows a comparison of the tool frame needed for a welding torch compared to the default tool coordinate system of the robot. By default the tool frame is set to the face-plate of the robot. The face-plate is located on the end of J6 of the robot (see figure 5a). The origin of the tool frame needs to be moved to the point (location and orientation) at which work is being done. This is called the Tool Center Point (TCP). For a welding application, this is the tip of the wire. To navigate to the menu to change the tool frame select the following:

- Menu → Setup → Type (F1) → Frames



(a) Tool Frame Menu



(b) Six Point Tool Frame Setup

Figure 28: FANUC Tool Frame Setup

Figure 28 shows the teach pendant screens used to setup the tool frame of the robot. Because the welding torch tool center point has a different location and orientation, the six point tool frame method needs to be used. This method uses three points to define the direction vector of the tool and three points to define the location of the tool center point. Once completed this tool frame should be used in all welding programs.

10.2.4 Host Communication Setup

The host communication setup screen in a FANUC robot is used to establish the network communication settings of the robot (i.e. IP adress and Subnet Mask). You can navigate to this screen via the teach pendant using the following instructions:

- Menu → Setup → Type (F1) → Host Comm → TCP/IP

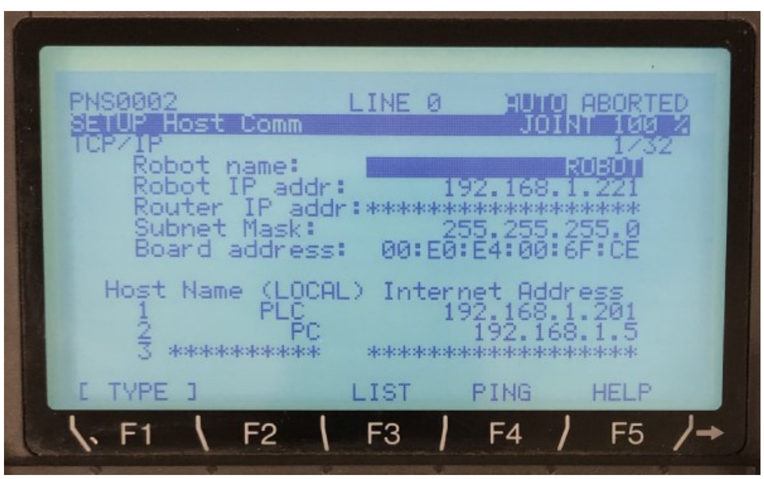


Figure 29: Host Communication Setup

Figure 29 shows the screen where the robot IP address and subnet mask will be configured along with the device IP addresses that will be communicating with the robot. As shown in figure 29 the robot is set up to communicate with the PLC and a PC (for troubleshooting). Ping (F4) will allow the robot to ping the device on the network to verify communication.

10.2.5 Ethernet Adapter Configuration

To communicate signals from the robot to external devices over Ethernet IP it is required that the Ethernet Adapter is setup using the following procedure:

- Menu → Setup → Type (F1) → Ethernet IP

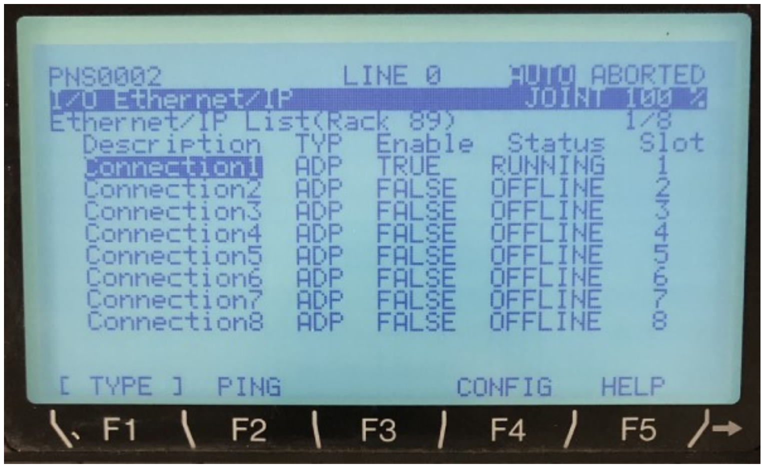


Figure 30: Ethernet Adapter Selection

Figure 30 shows the available Ethernet adapters to the robot. In this system only "Connection1" will be used to communicate with the PLC. Select CONFIG (F4) to configure the adapter.

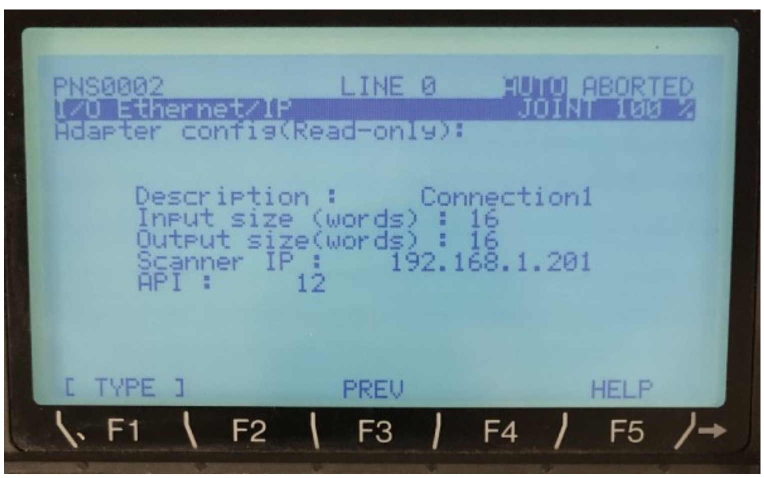


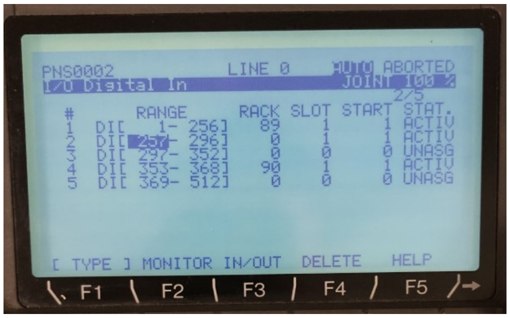
Figure 31: Ethernet Adapter Config

Figure 31 shows the configuration options for the adapter. In this system 16 words are transferred between the PLC and robot. Each word contains 16 bits. The "Scanner IP" is auto populated when connected to the PLC. The "API" section stands for "Actual Packet Interval" and shows that the 16 words are sent and received every 12 milliseconds.

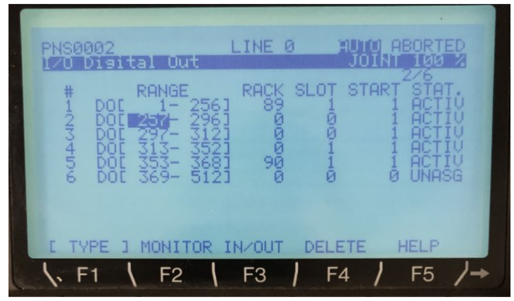
10.2.6 Digital I/O Configuration

The number of digital inputs and outputs required for the system need to be allocated using the Digital IO configuration screen on the teach pendant. In this system 16 words containing 16 bits each are being transferred between the robot and PLC meaning that 256 bits need to be allocated to Ethernet IP communication ($16 * 16 = 256$).

- Menu → IO → Type (F1) → Digital → Config (F4)



(a) Digital Input Configuration



(b) Digital Output Configuration

Figure 32: Digital I/O Configurations

Figure 32 shows the digital input and output configurations of the robot. The "Rack" column refers to the communication protocol being used (Rack 89 = Ethernet IP, Rack 90 = Arc Link). In this system there is communication between robot and PLC using Ethernet IP and between the robot and welder using Arc Link.

10.2.7 User Operator Panel Bits (UOP)

Fanuc robots include a set of user operator panel signals that allow the robot to be controlled by an external device (PLC) while also providing feedback to the device. The specific signals and their descriptions can be found below in Figures 33 and 34.

User Operator Panel (UOP) Input Signals		
UO#	Label	Description
UI[1]	IMSTP	Must be on for robot to operate
UI[2]	HOLD	Must be on for robot to operate
UI[3]	SFSPD	Must be on for robot to operate
UI[4]	CSTOPI	Abort ALL Tasks
UI[5]	FAULT RESET	System fault reset
UI[6]	START	Resumes Paused Program
UI[7]	HOME	Run Home Macro
UI[8]	ENBL	Must be on for Remote Operation
UI[9]	RSR/PNS1	Program Select Number
UI[10]	RSR/PNS2	Program Select Number
UI[11]	RSR/PNS3	Program Select Number
UI[12]	RSR/PNS4	Program Select Number
UI[13]	PNS5	Program Select Number
UI[14]	PNS6	Program Select Number
UI[15]	PNS7	Program Select Number
UI[16]	PNS8	Program Select Number
UI[17]	PNSTROBE	Set Selected Program
UI[18]	PROD_START	Start Selected Program

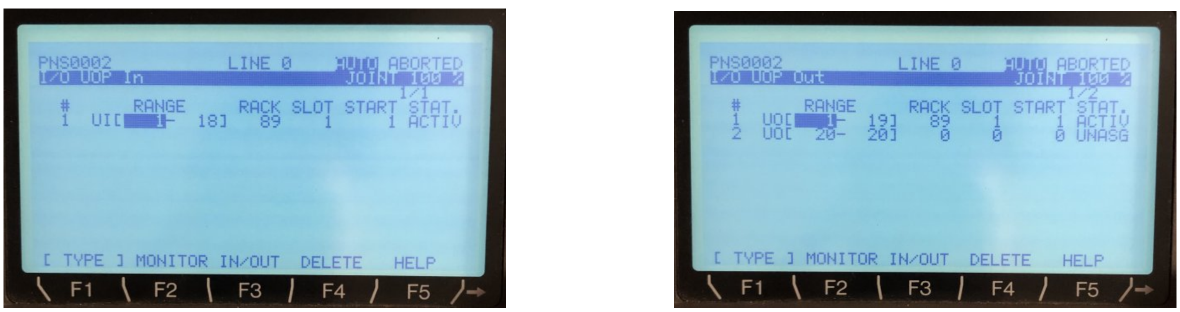
Figure 33: UOP Input Signals

User Operator Panel (UOP) Output Signals		
UO#	Label	Description
UO[1]	CMD Enabled	Robot is in Remote Condition and not faulted
UO[2]	System Ready	System Ready - Servo Motors are On
UO[3]	Program Running	A Program is Running
UO[4]	Program Paused	A Program is Paused
UO[5]	Motion Held	Hold Input is Off
UO[6]	Fault	A Program is in Error Condition
UO[7]	At Perch	Robot is at the Pre-defined Perch Position
UO[8]	TP Enabled	Teach Pendant Switch is On
UO[9]	Batt Alarm	Battery Low Voltage Alarm
UO[10]	Busy	Robot is Executing a Program
UO[11]	ACK/SNO1	Corresponding RSR is On Or PNS Selected Program Number
UO[12]	ACK/SNO2	Corresponding RSR is On Or PNS Selected Program Number
UO[13]	ACK/SNO3	Corresponding RSR is On Or PNS Selected Program Number
UO[14]	ACK/SNO4	Corresponding RSR is On Or PNS Selected Program Number
UO[15]	ACK/SNO5	Corresponding RSR is On Or PNS Selected Program Number
UO[16]	ACK/SNO6	Corresponding RSR is On Or PNS Selected Program Number
UO[17]	ACK/SNO7	Corresponding RSR is On Or PNS Selected Program Number
UO[18]	ACK/SNO8	Corresponding RSR is On Or PNS Selected Program Number
UO[19]	SNACK	Pulses when Program Select has been made

Figure 34: UOP Output Signals

To configure these bits follow the instructions below:

- Menu → IO → UOP → Type (F1) → CONFIG (F3)



(a) UOP Input Configuration

(b) UOP Output Configuration

Figure 35: UOP I/O Configuration

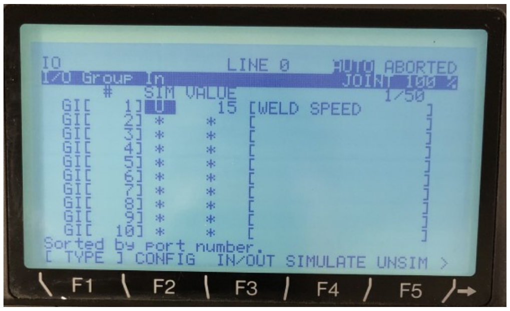
Figure 35 shows the teach pendant screens used to configure both the input and output UOP bits. This configuration is similar to the Digital I/O configuration seen in section 10.2.6, the "Rack" and "Slot" values should be the same. The "Start" point can be any number desired although in this system it was organized so that the first section of inputs and outputs would consist of the UOP bits.

The configured UOP bits are not added in addition to the digital I/O but instead are mapped on top of the digital I/O. The total number of digital inputs and outputs can be thought of as the full pie and the UOP bits will use part of that pie.

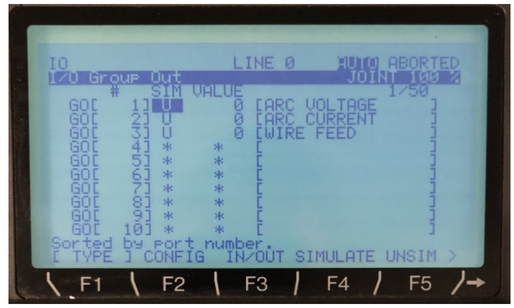
10.2.8 Group I/O Configuration

In the FANUC software version 6.4 explicit messaging via Ethernet IP is not an option, therefore Group I/O are used to send integer values to and from the robot.

- Menu → IO → Type (F1) → Group



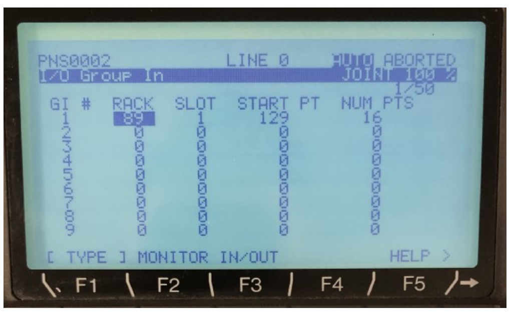
(a) Group Inputs Used in System



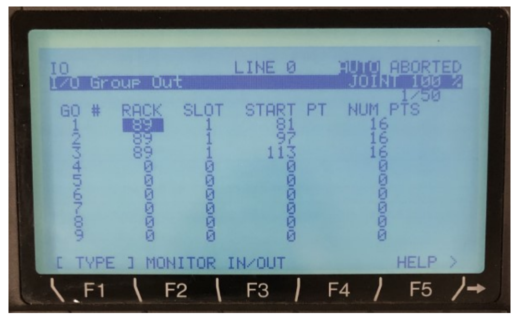
(b) Group Outputs Used in System

Figure 36: Group I/O Used in System

Figure 36 shows the group inputs and outputs used in the system. In order to configure the the group inputs and outputs select CONFIG (F4).



(a) Group Input Configuration



(b) Group Output Configuration

Figure 37: Group I/O Configurations

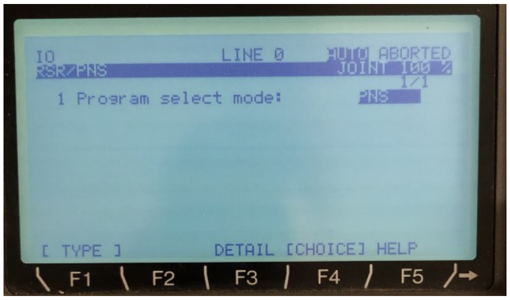
Figure 37 shows the teach pendant screen used to allocate bits to each input or output. The Rack and Slot will remain the same as configured in the Digital I/O section (Section 10.2.6. The "START PT" refers to the bit number that the group output will begin and the "NUM PTS" refers to the number of bits used for the input or output. In this system 16 bits are used for each group input and output.

Similar to the UOP Configuration (Section 10.2.7), the Group I/O will not add additional digital I/O but instead use a section of bits from the digital I/O. This makes it crucial to organize where bits are allocated.

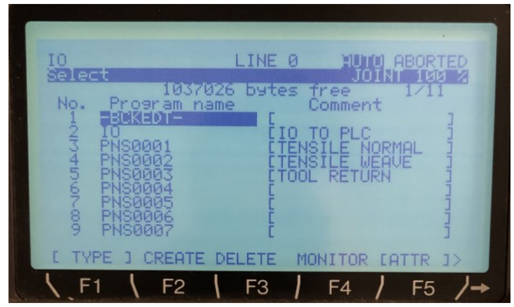
10.2.9 PNS Program Selection

The PNS Program select is one of the options that can be used to select and start a FANUC Robot TP Program in Auto Mode from an external device (PLC or HMI). The feature utilizes the UOP Inputs bits for the selection and starting of the program and then UOP Output bits for confirmation the program has been selected. To set PNS as the program select method select the following:

- Menu → Setup → Type (F1) → RSR/PNS → Choice (F4)



(a) PNS Setup



(b) Teach Pendant Programs

Figure 38: PNS and TP Program Naming

Figure 38a shows the screen where the PNS option is selected on the teach pendant. Once this option is selected the UOP input bits 9-16 seen in Figure 33 are used to create an 8 bit binary number that the robot uses to select the referenced program.

- UI[9] is the least significant bit (LSB) or rightmost bit in the binary number
- UI[16] is the most significant bit (MSB) or leftmost bit in the binary number
- The referenced program name needs to follow the naming convention of "PNSxxxx" (see Figure 38b for examples)

UI Number	UI[16]	UI[15]	UI[14]	UI[13]	UI[12]	UI[11]	UI[10]	UI[9]				
Bit Value	Off	Off	Off	Off	On	Off	Off	On				
Conversion	0	0	0	0	8	0	0	1	=	9	OR	PNS0009

Figure 39: PNS Conversion Example

Figure 39 shows an example conversion of how to robot converts the Boolean input bits to an integer value. An example sequence of operations can be seen below:

- Make sure UO[1] CMDENBL is high
  - CMDENBL requires the robot to be in auto mode, remote mode, and have no faults (otherwise you will not be able to select a program)
- Set desired bits to be high out of UI[9 – 16]
- Toggle UI[17] PNSTROBE to set this program as the selected program
- UO[19] SNACK will pulse when UI[17] PNSTROBE is toggled, this can be used as a handshake to confirm the program was actually selected
- UO[11 – 18] can be used as a confirmation that the correct program has been selected
  - They will echo the UI[9 – 16] bits once UI[17] PNSTROBE has been toggled
- UI[18] PRODSTART can be triggered to run the selected program

Figure 40 below shows the timing diagram for the PNS program selection:

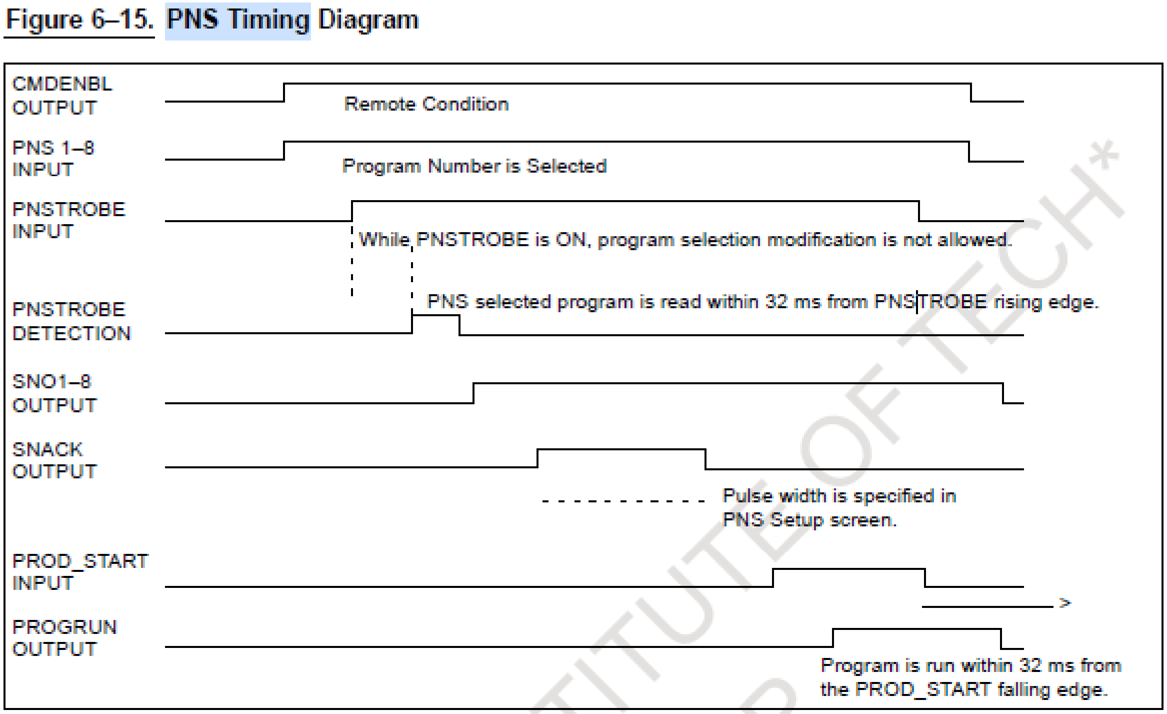


Figure 40: PNS Timing Diagram

10.2.10 Background Logic Program

Background logic programs can be a very useful way to transfer I/O between external devices and the robot while other programs are running in parallel. In this system a background logic program was utilized to transfer weld I/O from the robot to the PLC and vice versa. To setup a background program select the following:

- Menu → Setup → Type (F1) → BG Logic → Choice (F4) → Select the desired TP program → RUN (F2)

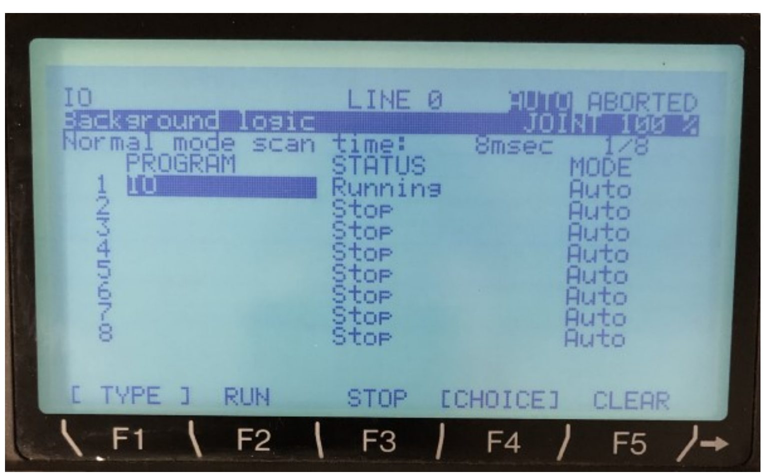


Figure 41: Background Logic Program Setup

Figure 41 shows the teach pendant setup screen that will be used to select the background logic program

(Note: the program must be "stopped" to edit it).

Line #	Program Statement	Description
1	GO[1: ARC VOLTAGE] = (AI[7])	Allow PLC to access weld voltage from welder
2	GO[2: ARC CURRENT] = (AI[8])	Allow PLC to access weld current from welder
3	GO[3: WIRE FEED] = (AI[9])	Allow PLC to access wire speed from welder
4	DO[356] = DI[49: WIRE INCH FORWARD]	Allow PLC to control wire inch forward
5	DO[357] = DI[49: WIRE INCH BACKWARD]	Allow PLC to control wire inch backward
6	R[10: WELD SPEED] = GI[1: WELD SPEED]	Allow PLC to control the robot weld speed

Figure 42: Background Logic Program used in System

Figure 42 shows the background logic program used in the system that allows the PLC to access weld data from the robot including the live voltage, current, and wire feed values. This also allows the PLC to control the wire feeder on the robot by inching the wire forward and backward when needed.

10.2.11 Selecting the Weld Process (Lincoln Electric)

The weld equipment setup menu allows the user to specify the kind of welding the equipment will perform. In this system a Lincoln Electric Power Wave 455M is used therefore the process selected will define the output characteristics of the welder. To change the welding process select the following:

- Menu → Setup → Type (F1) → Weld Equip

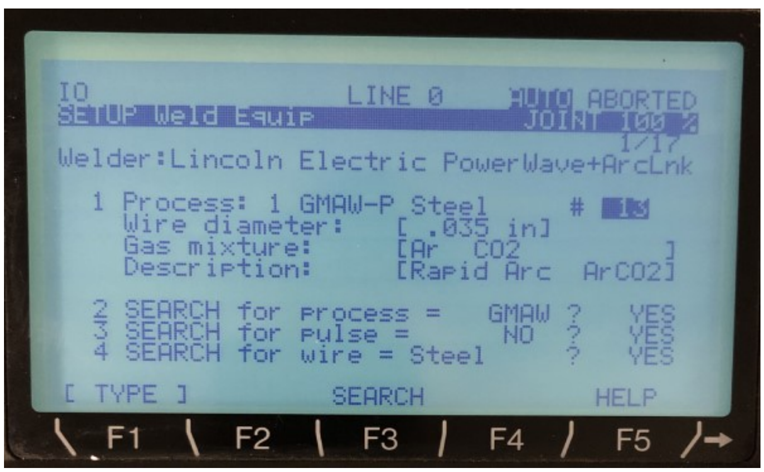


Figure 43: Weld Equipment Process Selection

Figure 43 shows the teach pendant screen that allows the weld process to be selected. Line items 2-4 allow the operator to select the type of process to search for in the welding power supply. The Lincoln Electric welding power supply has welding processes loaded in the welder that the robot is able to select from. To change the process select SEARCH (F3) which will allow different wire diameter, gas mixtures, and process characteristics to be selected. This system is using process number 13 which is the Rapid Arc process with .035" wire diameter and Argon/C02 gas mixture.

10.2.12 Welding Parameters

Weld schedules are used to control the welding parameters. The schedule defines the information that determines how the welding will be performed. The weld schedule information will vary depending on the weld equipment and process that are in use. To change the weld schedule data select the following:

- Data → Type (F1) → Weld Sched

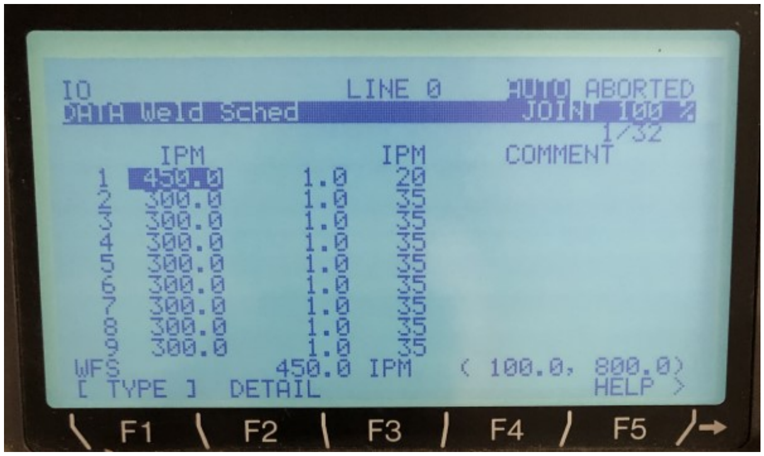


Figure 44: Weld Schedule Parameters

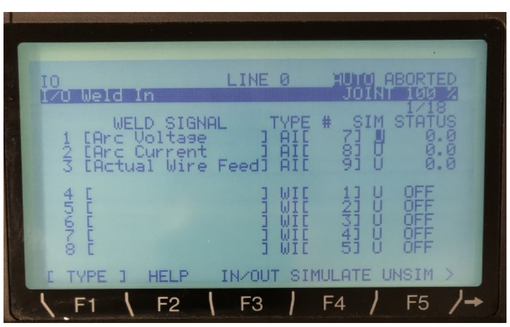
Figure 44 shows the teach pendant screen used to change the welding parameters for the weld. The far left column is the "WFS" or Wire Feed Speed value. This is the main control for the heat or current in the Rapid Arc process. The next column over is the "Trim" value. This is what controls the Arc length of the weld. The far right column is the travel speed of the robot during the weld. In this system the weld travel speed is indirectly controlled from the PLC using R[10] and the background logic program seen in Figure 42. Therefor this value in the weld schedule menu is not used.

Other than the welding travel speed, Weld Schedule parameters cannot be indirectly referenced by an external device. This required the teach pendant to be utilized to change the welding parameters.

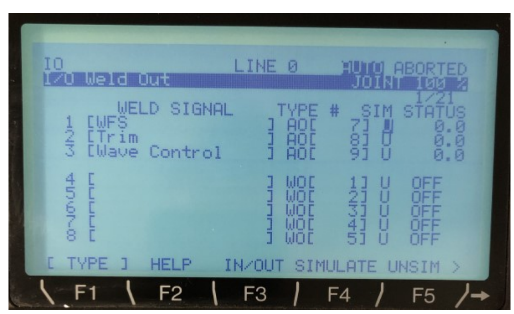
10.2.13 Weld I/O

To view the weld I/O available from the robot select the following:

- Menu → I/O → Type (F1) → Weld



(a) Weld Analog Inputs



(b) Weld Analog Outputs

Figure 45: Weld Analog I/O

Figure 45 shows both the analog inputs and outputs being transferred from the robot to the welder. Using the background logic program seen in Figure 42, the analog feedback signals were able to be accessed from the PLC.

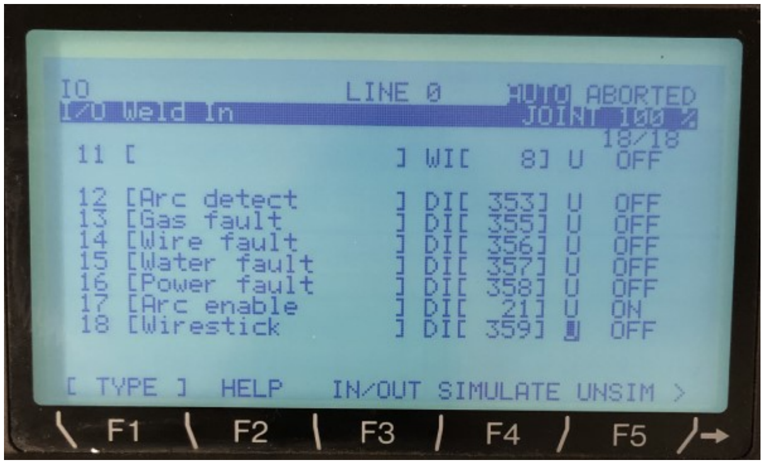


Figure 46: Remote Control of Weld Enable

Figure 46 shows the digital inputs available to the robot from the welder. Line 17 shows the input "Arc Enable". By configuring this signal to be controlled by DI[21], the PLC can control when the Arc is enabled. This allows the operator to control when the robot will weld vs dry run.

10.2.14 Weave Setup

The weave option in the Fanuc robot allows the TCP of the robot to move in a sine wave during the welding process. This can be used to increase penetration and material output during a weld. To access the setup screen, select the following:

- Menu → Setup → Type (F1) → Weave

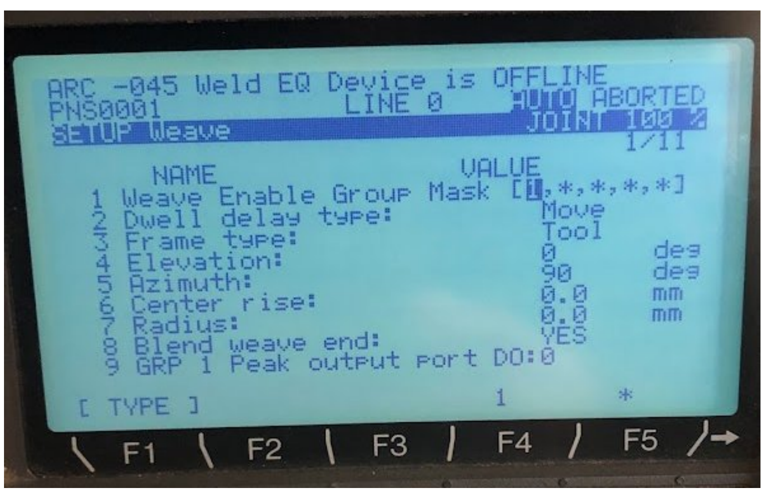


Figure 47: Weave Setup Screen

Figure 47 shows the teach pendant screen used to setup the weave. Weaving always will use the robots tool frame as the reference plane so it is important to have an accurate tool frame setup. The elevation (line 4) is used to change the weaving plane without changing the tool orientation. By setting the elevation to 90, the weave motion would be in the Z axis (up and down) [4]. The Azimuth (line 5) is used to change the angle of the weave if the tool cannot be rotated. This was set to 90deg in this system to allow the robot to weave perpendicular to the weld path of the tensile sample.

10.2.15 Weave Parameters

Similar to the welding parameter section (10.2.12), weave parameters are also stored in schedules in the robot. These parameters determine how the weave is performed. To change the weaving parameters, select the following:

- Data → Type (F1) → Weave Schedule

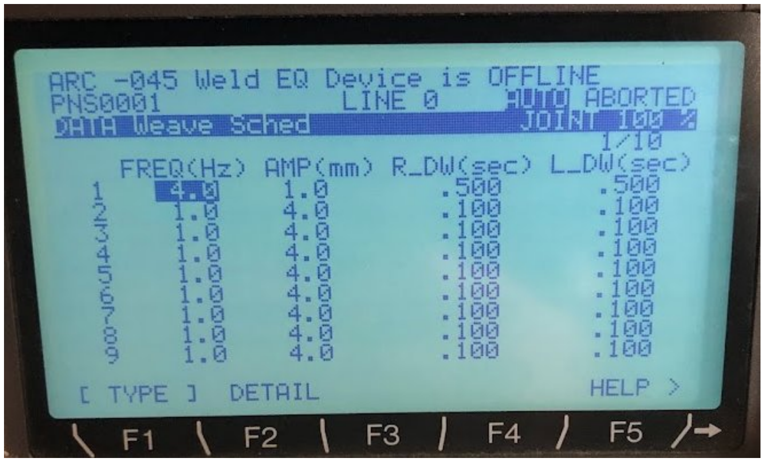


Figure 48: Weave Schedule Screen

Figure 48 shows the teach pendant screen used to control the weave schedule. The weave can be thought of as a sine wave. The FREQ (frequency) determines the cycles per second (hz). The AMP (amplitude) determines the distance from the center line of the weave to either peak. The R_DW and L_DW determine the right and left dwell times. Dwell times are the amount of time the robot delays at either side of the weld at the peak of the sine wave.

Weave Schedule parameters cannot be indirectly referenced by an external device. This requires the teach pendant to be utilized to change the weave parameters.

10.2.16 Welding Programs

Line #	Program Statement	Description
1	DO[33: TASK STARTED] = ON	Signal to PLC that the task has started
2	DO[34: TASK COMPLETE] = OFF	Signal to PLC that the task has not been completed
3		
4	UTOOL_NUM=2	Set the correct Tool Frame for the welding torch
5	UFRAME_NUM=0	Set the User Frame to the World Frame
6		
7	PR[2: APPROACH] = PR[3: WELD START]	Set the weld approach position register 10mm above the weld start position register
8	PR[2,3: APPROACH] = PR[3,3: WELD START] + 10	
9		
10	PR[5: DEPART] = PR[4: WELD END]	Set the weld depart position register 10mm above the weld end position register
11	PR[5,3: DEPART] = PR[4,3: WELD END] +10	
12		
13	J PR[1: HOME] 100% FINE	Move to home position
14	J PR[2: APPROACH] 100% FINE	Move to weld approach position
15	L PR[3: WELD START] 800 mm/sec FINE	Move to weld start position
:	ARC START[1]	Start arc using weld schedule number 1
16	L PR[4: WELD END] R[10: WELD SPEED] in/min FINE	Move to weld end point using register 10 to determine the travel speed
:	ARC END[1]	End arc using weld schedule 1
17	L PR[5: DEPART] 800 mm/sec FINE	Move to weld depart position
18	J PR[1: HOME] 100% FINE	Move back to home position
19		
20	DO[33: TASK STARTED] = OFF	Signal to PLC that the task is no longer started
21	DO[34: TASK COMPLETE] = ON	Signal to PLC that the task is complete

Figure 49: Robot Program for a Normal Weld

Line #	Program Statement	Description
1	DO[33: TASK STARTED] = ON	Signal to PLC that the task has started
2	DO[34: TASK COMPLETE] = OFF	Signal to PLC that the task has not been completed
3		
4	UTOOL_NUM=2	Set the correct Tool Frame for the welding torch
5	UFRAME_NUM=0	Set the User Frame to the World Frame
6		
7	PR[2: APPROACH] = PR[3: WELD START]	Set the weld approach position register 10mm above the weld start position register
8	PR[2,3: APPROACH] = PR[3,3: WELD START] + 10	
9		
10	PR[5: DEPART] = PR[4: WELD END]	Set the weld depart position register 10mm above the weld end position register
11	PR[5,3: DEPART] = PR[4,3: WELD END] +10	
12		
13	J PR[1: HOME] 100% FINE	Move to home position
14	J PR[2: APPROACH] 100% FINE	Move to weld approach position
15	L PR[3: WELD START] 800 mm/sec FINE	Move to weld start position
:	ARC START[1]	Start arc using weld schedule number 1
16	Weave Sine[1]	Start Weave schedule number 1
17	L PR[4: WELD END] R[10: WELD SPEED] in/min FINE	Move to weld end point using register 10 to determine the travel speed
:	ARC END[1]	End arc using weld schedule 1
18	Weave End[1]	End weave schedule number 1
19	L PR[5: DEPART] 800 mm/sec FINE	Move to weld depart position
20	J PR[1: HOME] 100% FINE	Move back to home position
21		
22	DO[33: TASK STARTED] = OFF	Signal to PLC that the task is no longer started
23	DO[34: TASK COMPLETE] = ON	Signal to PLC that the task is complete

Figure 50: Robot Program for a Weave Weld

Figures 49 and 50 are the programs used in this system to weld the tensile samples. Both programs utilize the same position registers (variables that contain position data), the only difference is the presence or absence of the weave by the robot. At the top and bottom of each program DO[33] and DO[34] are toggled on and off in order to provide feedback to the PLC that the program is in progress or complete.

10.2.17 Tooling Return Program

Line #	Program Statement	Description
1	DO[33: TASK STARTED] = ON	Signal to PLC that the task has started
2	DO[34: TASK COMPLETE] = OFF	Signal to PLC that the task has not been completed
3		
4	UTOOL_NUM=2	Set the correct Tool Frame for the welding torch
5	UFRAME_NUM=0	Set the User Frame to the World Frame
6		
7	PR[10: CURRENT POS] = LPOS	Set PR[10] to the current robot position
8	R[5: CURRENT X] = PR[10,1: CURRENT POS]	Set R[5] equal to the current robot x position
9	R[6: CURRENT Y] = PR[10,2: CURRENT POS]	Set R[6] equal to the current robot y position
10	R[5: CURRENT Z] = PR[10,3: CURRENT POS]	Set R[7] equal to the current robot z position
11		
12	IF R[6: CURRENT Y] < 280, JMP LBL[1]	Check to see if robot is close to welding fixture
13	IF R[6: CURRENT Y] >= 280, JMP LBL[2]	
14		
15	LBL[1]	If robot is not close to fixture, move directly to home position
16	J PR[1: HOME] 25% FINE	
17	JMP LBL[10]	
18		
19	LBL[2]	If robot is close to fixture, check the z height of the robot
20	IF R[7: CURRENT Z] < 120, JMP LBL[3]	
21	IF R[7: CURRENT Z] >= 120, JMP LBL[4]	
22		
23	LBL[3]	If robot z height is not clear of fixture:
24	PR[10,3: CURRENT POS] = 120	Set z height of current position register equal to 120 (clear height)
25	L PR[10: CURRENT POS] 100 mm/sec FINE	Move to the updated position
26	J PR[1: HOME] 25% FINE	Move home
27	JMP LBL[10]	
28		
29	LBL[4]	If robot z height is clear of fixture, move directly home
30	J PR[1: HOME] 25% FINE	
31	JMP LBL[10]	
32		
33	LBL[10]	
34	DO[33: TASK STARTED] = OFF	Signal to PLC that the task is no longer started
35	DO[34: TASK COMPLETE] = ON	Signal to PLC that the task is complete

Figure 51: Robot Program for Tooling Return

"Tooling Return" programs are used to recover the robot from any fault and bring it back to a known position to restart the program. There are various ways to accomplish this although because the simplicity of the cell, a method of comparing the current robot position to world coordinates was used. If the robot is in an unsafe position to move to the home position, the program will move the robot to a safe position before moving home.

This is useful whenever there is an arc fault to allow for better access to the welding torch to asses the problem.

10.3 PLC Design

The PLC used in this system is an Allen Bradley 5069-L306ER using software version 33.12. The PLC includes one 16 point sinking input module and one 16 point sourcing output module. The PLC is acting as the brain of the system by making the decision whether the robot is able to execute a program. It is reading inputs from the HMI and feedback from the robot.

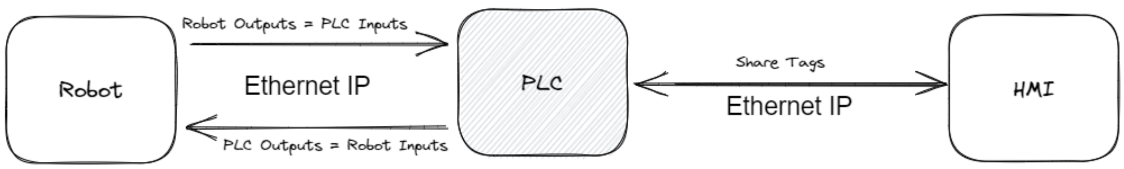


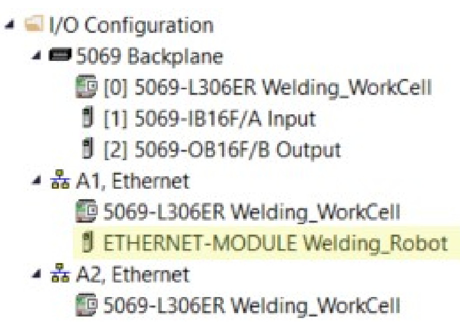
Figure 52: PLC Communication Overview

Figure 52 above helps to show which devices the PLC is directly communicating with. There are some simple setup procedures needed to allow the PLC to communicate with the Fanuc robot over Ethernet I/P.

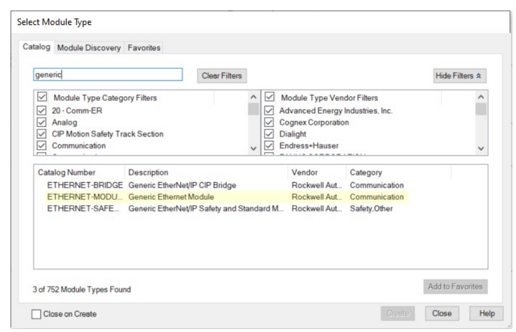
10.3.1 Generic Ethernet Module Setup

In Studio 5000 an Ethernet module can be created to allow the PLC and robot to consistently read and write implicit I/O data. In this system a Generic Ethernet Module was used for simplicity and because there was no EDS file available. The following instructions will show how to setup this module:

- Right click on "A1, Ethernet" → New Module → Search "generic" → Select the highlighted option in Figure 53b



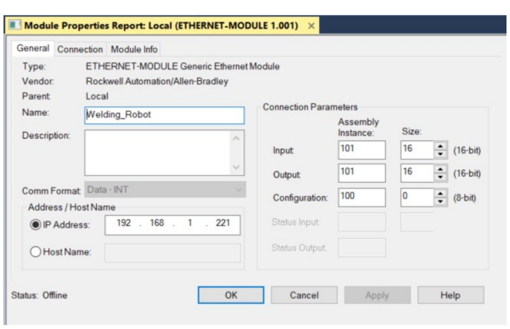
(a) Robot Ethernet Module in Tree



(b) Selecting a Generic Ethernet Module

Figure 53: Creating a Generic Ethernet Module

Figure 53a shows what the module will look like in the ethernet tree when created.



(a) Generic Ethernet Module Properties

Table 3–3. Adapter Configuration Summary

ITEM	DESCRIPTION
Vendor ID	356
Product Code	2
Device Type	12
Communication Format	Data – INT
Input Assembly Instance	101–108
Input Size	User Configurable, Set in 16-bit Words
Output Assembly Instance	101–108
Output Size	User Configurable, Set in 16-bit Words
Configuration Instance	100
Configuration Size	0

(b) Adapter Configuration Data from FANUC Manual [5]

Figure 54: Setting Ethernet Module Properties

Figure 54a shows the general properties that need to be input for the module to communicate with the robot. Make sure the network portion of the IP address (first 3 octets) match that of the PLC. The values that need to be placed in the "Connection Parameters" section are different for every robot model. They can be found in the Ethernet IP setup manual provided by Fanuc (see [5]). 54b shows the table that was used to find these values for the RJ3iB controller.

Once the Ethernet Module has been setup and is running, you will find the I/O from the robot available in the controller tags section of the PLC:

◢ Welding_Robot:I	{...}	{...}		AB:ETHERNET_MODULE_I...	
◢ Welding_Robot:I.Data	{...}	{...}	Decimal	INT[16]	
▸ Welding_Robot:I.Data[0]	4099		Decimal	INT	
▸ Welding_Robot:I.Data[1]	8		Decimal	INT	
▸ Welding_Robot:I.Data[2]	2		Decimal	INT	
▸ Welding_Robot:I.Data[3]	0		Decimal	INT	
▸ Welding_Robot:I.Data[4]	0		Decimal	INT	
▸ Welding_Robot:I.Data[5]	0		Decimal	INT	GO[5] - Arc Voltage
▸ Welding_Robot:I.Data[6]	0		Decimal	INT	GO[6] - Arc Current
▸ Welding_Robot:I.Data[7]	0		Decimal	INT	GO[7] - Actual Wire Feed
▸ Welding_Robot:I.Data[8]	0		Decimal	INT	
▸ Welding_Robot:I.Data[9]	0		Decimal	INT	
▸ Welding_Robot:I.Data[10]	0		Decimal	INT	
▸ Welding_Robot:I.Data[11]	0		Decimal	INT	
▸ Welding_Robot:I.Data[12]	0		Decimal	INT	
▸ Welding_Robot:I.Data[13]	0		Decimal	INT	
▸ Welding_Robot:I.Data[14]	0		Decimal	INT	
▸ Welding_Robot:I.Data[15]	0		Decimal	INT	

Figure 55: PLC Inputs from Robot

Figure 55 shows all of the PLC inputs from the robot (meaning robot digital outputs). The same is true with the PLC outputs to the robot (meaning robot digital inputs).

10.3.2 PLC to Robot I/O Mapping Method

To organize the digital I/O mapping between the PLC and robot, the following excel spreadsheet was used:

	PLC--> Robot (PLC Output, Robot Input)	Robot Address	Robot Label	Description
Word 0	Welding_Robot:O.Data[0].0	DI 1	UOP - IMSTP	Must be on for robot to operate
	Welding_Robot:O.Data[0].1	DI 2	UOP - HOLD	Must be on for robot to operate
	Welding_Robot:O.Data[0].2	DI 3	UOP - SFSPD	Must be on for robot to operate
	Welding_Robot:O.Data[0].3	DI 4	UOP - CSTOPI	Abort ALL Tasks
	Welding_Robot:O.Data[0].4	DI 5	UOP - FAULT RESET	System fault reset
	Welding_Robot:O.Data[0].5	DI 6	UOP - START	Resumes Paused Program
	Welding_Robot:O.Data[0].6	DI 7	UOP - HOME	Run Home Macro
	Welding_Robot:O.Data[0].7	DI 8	UOP - ENBL	Must be on for Remote Operation
	Welding_Robot:O.Data[0].8	DI 9	UOP - RSR/PNS1	Program Select Number
	Welding_Robot:O.Data[0].9	DI 10	UOP - RSR/PNS2	Program Select Number
	Welding_Robot:O.Data[0].10	DI 11	UOP - RSR/PNS3	Program Select Number
	Welding_Robot:O.Data[0].11	DI 12	UOP - RSR/PNS4	Program Select Number
	Welding_Robot:O.Data[0].12	DI 13	UOP - PNS5	Program Select Number
	Welding_Robot:O.Data[0].13	DI 14	UOP - PNS6	Program Select Number
	Welding_Robot:O.Data[0].14	DI 15	UOP - PNS7	Program Select Number
	Welding_Robot:O.Data[0].15	DI 16	UOP - PNS8	Program Select Number
Word 1	Welding_Robot:O.Data[1].0	DI 17	UOP - PNSTROBE	Set Selected Program
	Welding_Robot:O.Data[1].1	DI 18	UOP - PROD_START	Start Selected Program
	Welding_Robot:O.Data[1].2	DI 19	Speed Override Select (bit 1)	Select Override Speed of Robot
	Welding_Robot:O.Data[1].3	DI 20	Speed Override Select (bit 2)	
	Welding_Robot:O.Data[1].4	DI 21	Arc Enable	Enable or disable welding (only available during remote mode)
	Welding_Robot:O.Data[1].5	DI 22		
	Welding_Robot:O.Data[1].6	DI 23		
	Welding_Robot:O.Data[1].7	DI 24		
	Welding_Robot:O.Data[1].8	DI 25		

Figure 56: Robot and PLC I/O Mapping

Figure 56 shows a portion of the spreadsheet used to organize the digital I/O mapping between the PLC and robot. This spreadsheet allowed the configuration of I/O in the robot much easier by showing which robot input/output corresponds to what PLC tag address.

10.3.3 Exporting PLC Tags for HMI Reference

When programming the HMI it is important that the tag values used are updated to match the PLC. One method of exporting these tags is by exporting a .L5X file from Studio 5000. This is done though selecting "Save as" on the PLC project and selecting the file type to be ".L5X".

10.4 HMI Graphics Design

The HMI used in this system is a Maple Systems CMT3092X. The software used to design the graphics was Easy Builder Pro version 6.07.01. Although this HMI is designed for machine control rather than process control, principles from High Performance HMI (section 4.3) were used when designing the graphics including the overview screen design and color schemes. The following sections describe the details of each HMI screen in the project.

10.4.1 Overview Screen

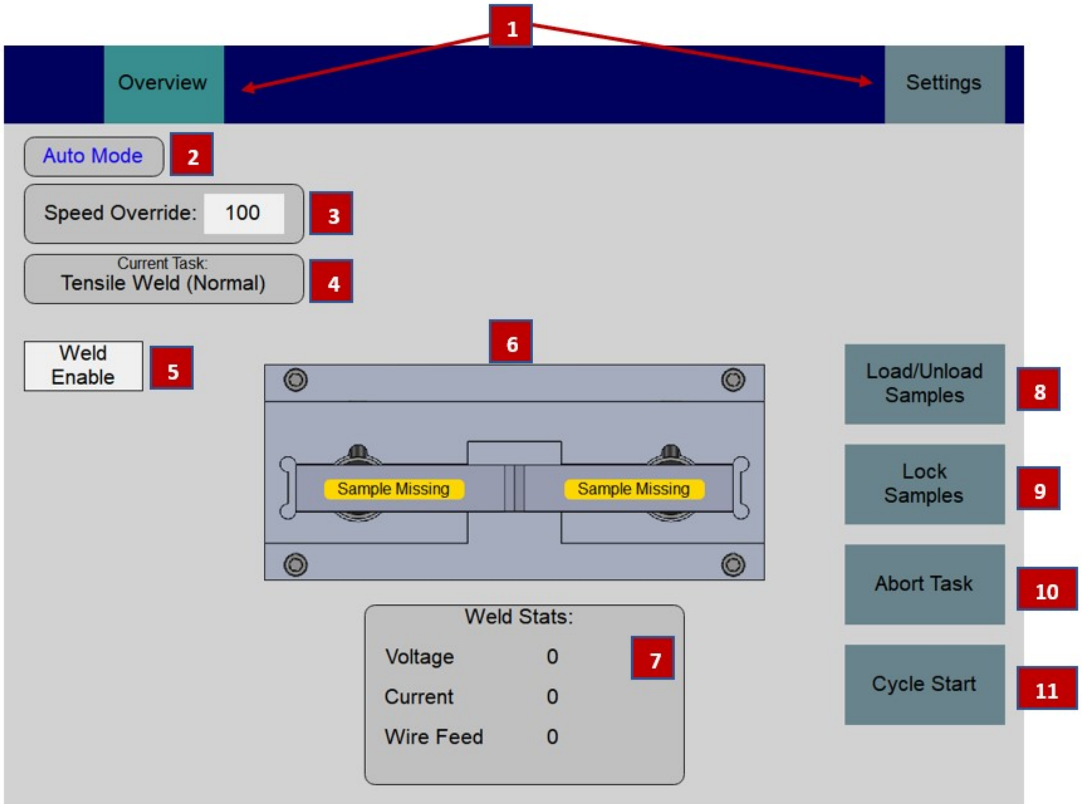
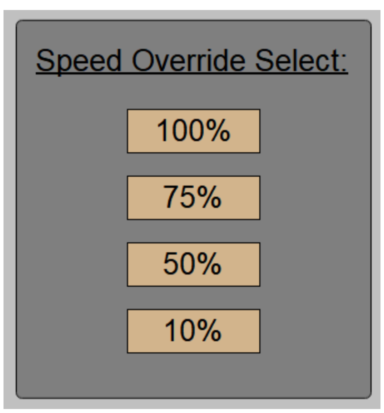


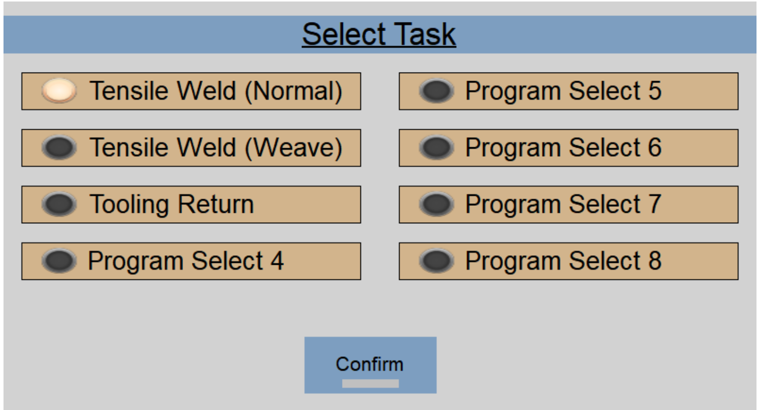
Figure 57: HMI Overview Screen

Figure 57 displays the system overview screen. This screen allows for an overall glance at the system status while also allowing quick access to various settings windows by simply selecting an element. The following list describes the function of each element:

1. These are the main navigation buttons, selecting either will bring the user to the designated screen. The color of the navigation button indicates whether it is the current screen.
2. This is a live display of what control state the robot controller is in (T1, T2, or Auto).
3. This is a display of the current robot speed override. By selecting the element it will display the popup display below, allowing the user to select a new speed override.



4. This is a display of the current task selected in the robot controller. By selecting this item it will display the popup display below, allowing the user to select a new program.



5. This element will toggle the Arc Enable bit in the robot (see Figure 46) to allow the operator to easily conduct dry runs to test the weld paths. When enabled, the system will automatically set the override speed of the robot to 100%.

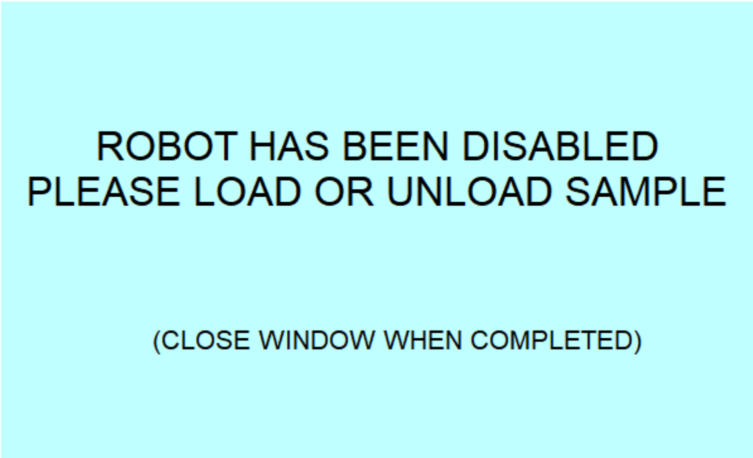
6. This element displays if the tensile samples are detected in the fixture or not. It clearly indicates when the samples are missing using a yellow background to ensure the operator notices.

7. This element displays the weld feedback from the robot prior to each weld. The data will be retained until the system is powered off or a new weld has been started.

8. This element allows the operator to load or unload the tensile samples from the fixtures. When selected the following items will occur:

   - Electromagnets will de-energize
   - Laser will turn on to allow the samples to be centered in the fixture
   - The light curtains will be de-activated allowing the user to break the beam without the faulting the robot
   - The robot will be disables ensuring the operator is safe in the work envelope.

   The following popup screen will be activated to let the operator know the cell is safe to enter:



9. This element will energize the electromagnets

10. This element is used to abort the current task. If the robot has a fault the during the weld, the current task needs to be aborted prior to selecting a new task (tooling return).

11. This element is used to execute the current program selected. There are certain conditions that need to be true within the PLC for the program to start (otherwise the element will be grayed out):

   - CMD Enable needs to be active
   - Tensile samples must be present
   - Tensile samples must be locked
   - No faults can be present

10.4.2 Settings Screen

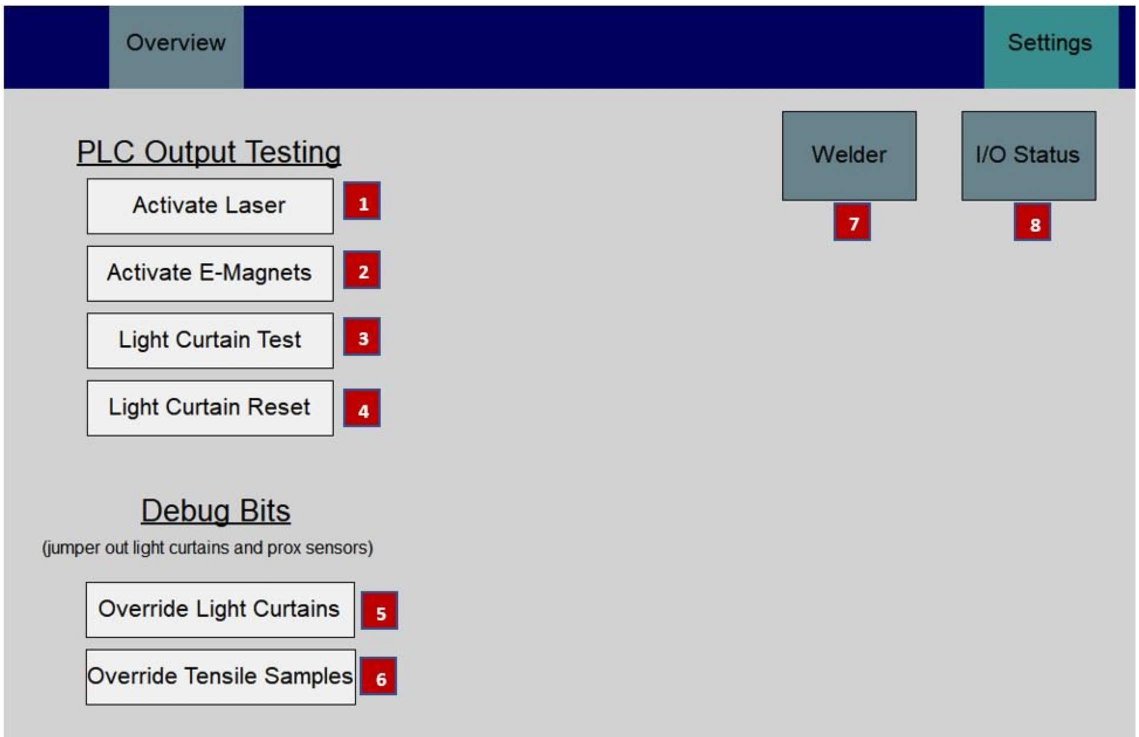


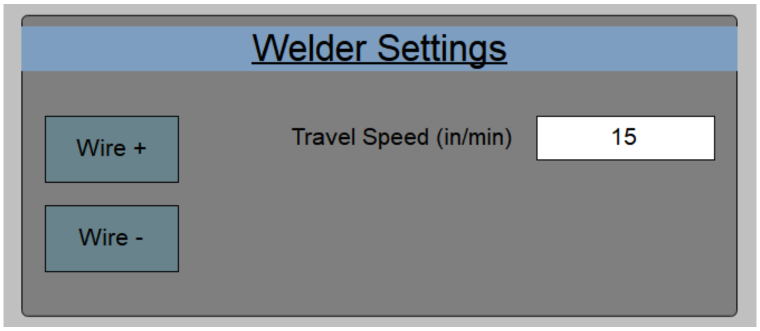
Figure 58: HMI Settings Screen

Figure 58 shows the HMI settings screen. This screen is to allow the operator to adjust settings of the robot and disable features of the system to allow for easier testing. The following list describes the function of each element:

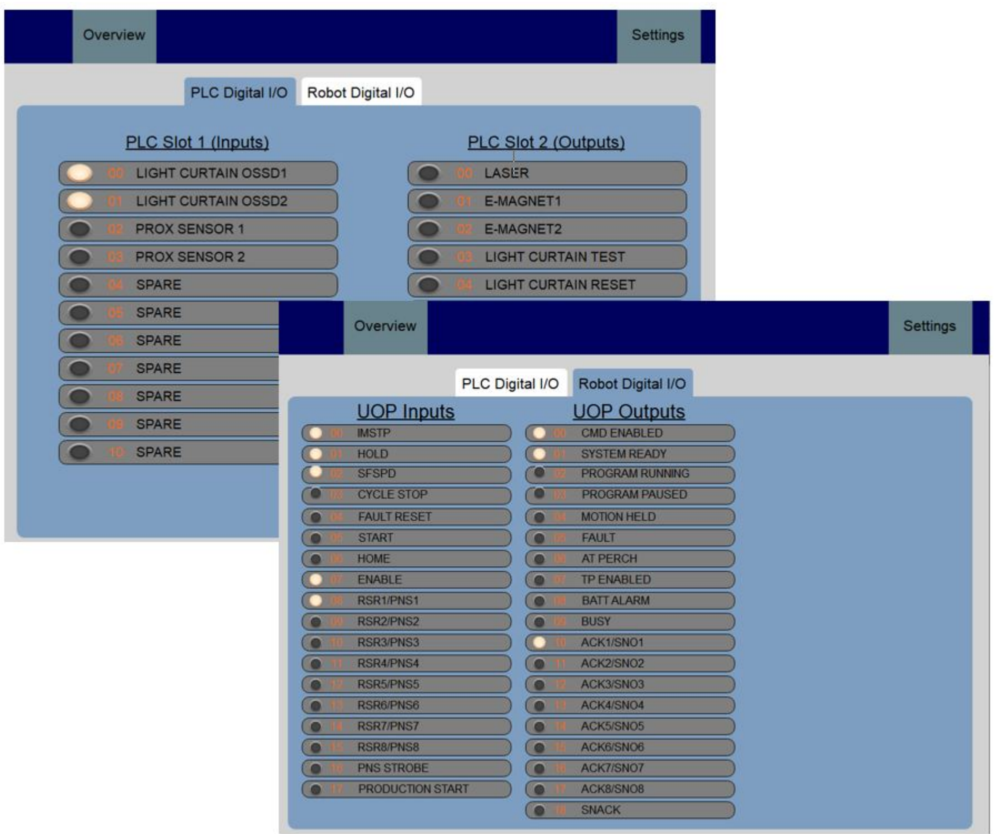
1. This element is used to test the 5V laser output from the PLC
2. This element is used to test the electromagnet PLC outputs
3. This element is used to fault the light curtain to test the emergency conditions
4. This element will reset the light curtain from a fault if the dip switches are set to manual reset mode. (light curtain is currently in auto reset mode)
5. This element will override the light curtains and allow the system to start for testing

6. This element will override the tensile samples and allow the system to start for testing

7. This element will open the following popup screen and allow the operator to change the weld travel speed and test the wire feeder on the robot. By holding the Wire + or Wire - buttons, the wire feeder will either feed or retract wire from the welding torch.



8. This element will navigate to the I/O Status screens:



11 Data Collection

The MTS 45/G Tesnile tester in the RIT Lab 1190 was used to test the ultimate tensile strength (UTS) of 10 robotic welded specimen. The Rapid Arc weld process with a Weave was used with the following parameters:

- WFS: 450
- Trim: 1
- Wave Control: 0
- Travel Speed: 20 in/min
- Weave Frequency: 4hz
- Weave Amplitude: 2mm
- Weave Dwell Times: .25sec

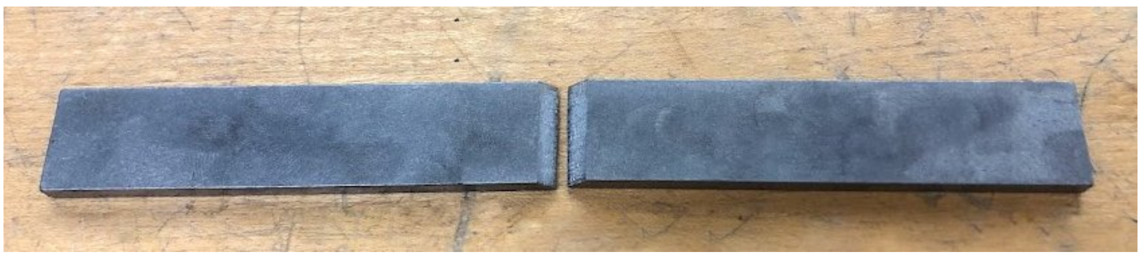


Figure 59: Tensile Sample Image

Figure 59 shows the weld specimen used. The samples are 1018 cold drawn steel with measurements of 3.5" x 0.75" x 0.188".

Student and instructor weld data was collected from previous semesters to compare the average ultimate tensile strength and repeatability to the robot results. (Note: the weld instructors are students who are experienced MIG welders).

12 Results

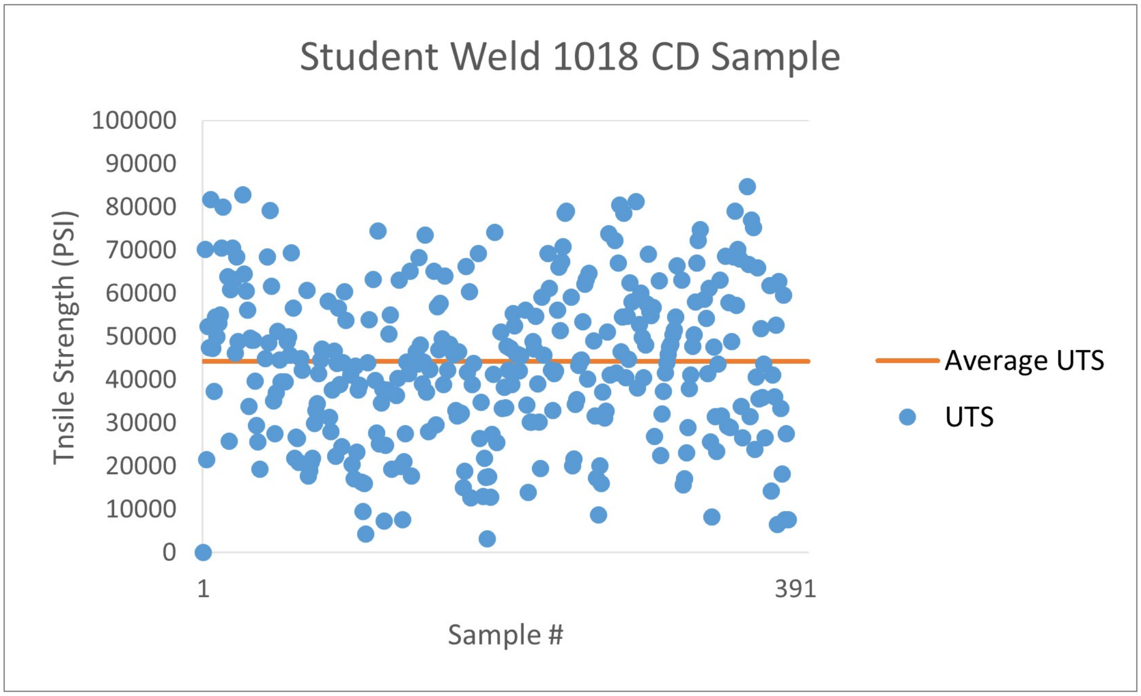


Figure 60: Student Weld Results

Figure 60 shows the distribution of UTS results from previous class students. The graph shows an average UTS of about 44,000 PSI and a standard deviation of about 18,500 PSI.

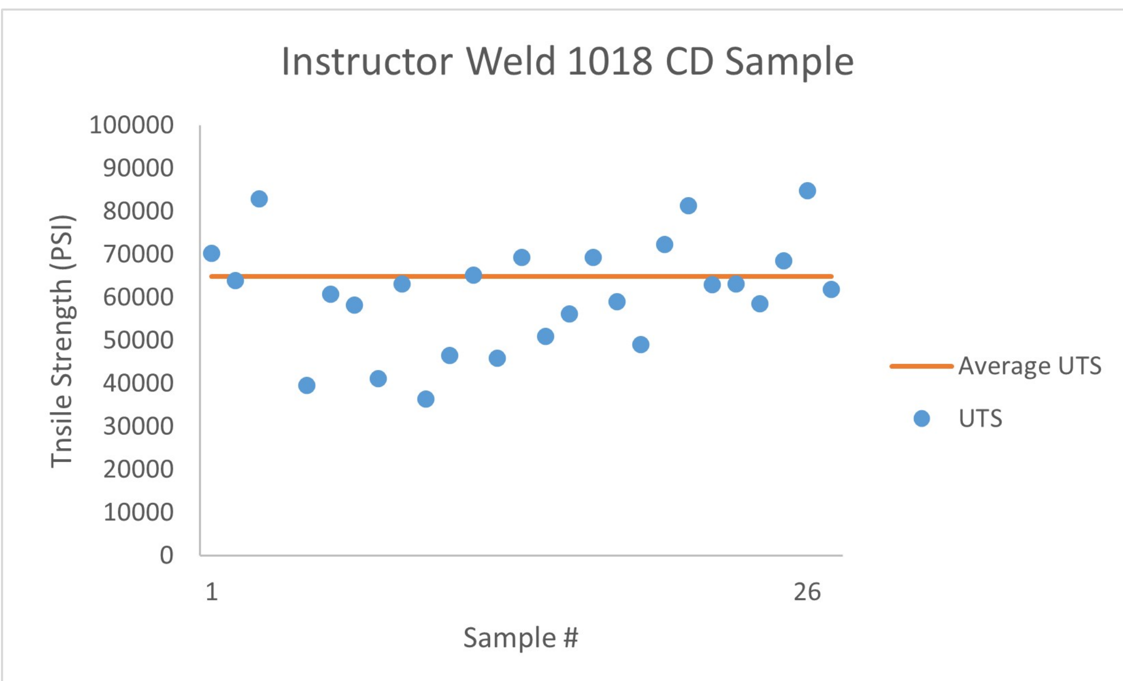


Figure 61: Instructor Weld Results

Figure 61 shows the distribution of UTS results from previous class weld instructors. The graph shows an average UTS of about 65,000 PSI and a standard deviation of about 13,000 PSI.

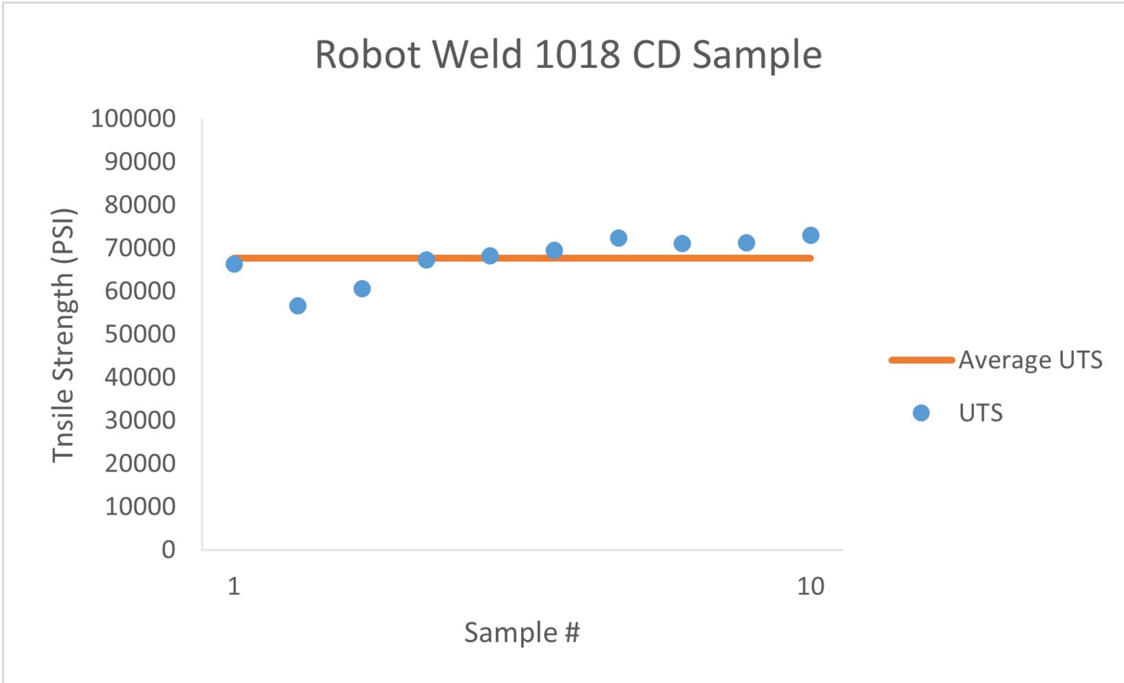


Figure 62: Robot Weld Results

Figure 62 shows the distribution of UTS results from the robot welds. The graph shows an average UTS of about 67,500 PSI and a standard deviation of about 5,000 PSI.

	Instructor Weld	Robot Weld	Student Weld
Average UTS (PSI)	64,833.30	67,642.45	44,242.06
Average STD (PSI)	12,781.33	5,271.32	18,571.84

Figure 63: UTS Comparison Data Table

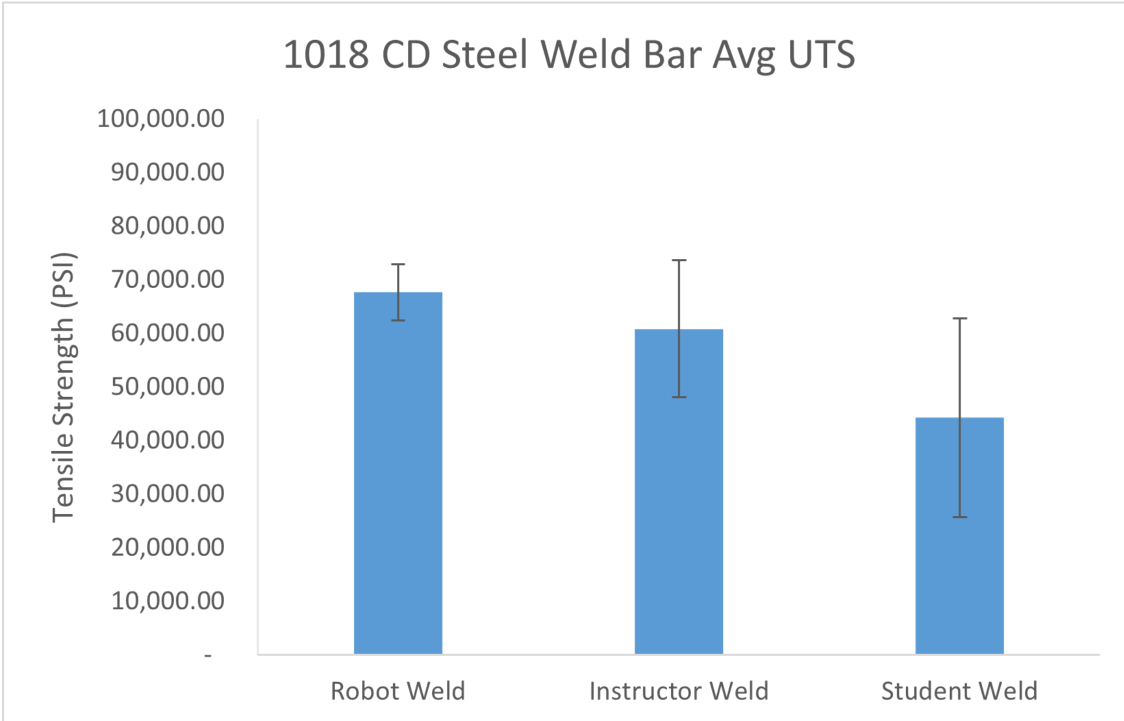


Figure 64: UTS Comparison Graph

Figures 63 and 64 show both the comparison data table and comparison graph of the welded specimen average tensile strength and standard deviation. The error bars seen in Figure 64 represent the standard deviation for that group. It can be seen that the robot weld resulted in an 11.2% increase in tensile strength and a 58.76% decrease in standard deviation when compared to the instructor weld data. It can also be seen that the robot weld resulted in an 52.89% increase in tensile strength and a 71.62% decrease in standard deviation when compared to the student weld data.

13 Discussion

13.1 Cell Design

The cell performed very well and the design process used was optimal for robotic workcell design.

1. Mechanical Design
2. Electrical / Hardware Design
3. Mechanical and Electrical Build
4. Software Design
5. Debug

Beginning with the mechanical design is very helpful to specify all components and ensure the operational expectations of the cell are met. The electrical design is the next portion that is required to ensure all control devices are selected and powered correctly. The electrical design is what really lays the groundwork for the software design of the system. The software design of the system was the longest portion of the project. The integration of an older robot with new technologies was a difficult but achievable task. The setup procedures seen in sections 10.2 and 10.3 include procedures that would be required to achieve the same result integrating a Fanuc robot with an Allen Bradley PLC on a different system.

The system was also designed to handle other projects since it is in a lab environment. Any safeguard requiring the tensile samples to be present for the robot to operate can be turned off from the settings screen of the HMI (section 10.4.2). This ensures that the PLC software does not need to be edited anytime another welding project is implemented. There are also 5 spare welding programs already setup to be selected using PNS (section 10.2.9) from the HMI that can be used for any other project.

It is always a challenge to design a system that can handle an unknown amount of expansion or future work. An area of improvement would be to find a more modular way to cleanly add additional sensor inputs and actuator outputs to the system.

13.2 Weld Performance

Overall the robot was able to out preform both the instructor and student historical weld data from previous semesters in average tensile strength and repeatability. This signifies that robotic welding can create the most repeatable welds in a lab environment. The sample size of the robotic welded samples was small with only 10 specimen, therefore a repeat of this test with a larger number of specimen would be beneficial.

Although the average tensile strength from the welded specimen was higher than that of the instructor data, it was not as high as expected based on some of the more impressive instructor welds. This may be for a variety of reasons but most likely due to the amount of material filled into the bevel groove.

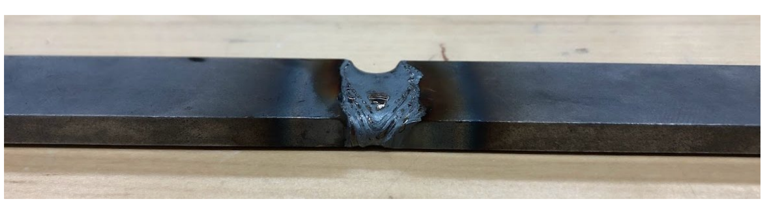


Figure 65: Top View Image of Robot Weld

Figure 66: Bottom View Image of Robot Weld

Figures 65 and 66 show images of a robot welded tensile sample. Figure 66 helps to show the lack of material on the rear side of the weld. The weave was used with the intent of filling the bevel groove with more material although more tuning needs occur to optimize the material fill.

An area of improvement would be to design an experiment to optimize the welding parameters to maximize the tensile strength of the welds.

14 Conclusion and Lessons Learned

This was a large project that started in August of 2022 and was completed in April of 2023. Over this time span and project I learned more than I ever imagined regarding FANUC robots and robotic welding. Below are some mistakes and lessons that I learned throughout the process:

- When completing the electrical schematic design I didn't wire the neutrals of each power supply to the terminal strip to bond them to ground. I instead had one of the power supplies power the PLC directly. This caused the digital inputs not to be recognized since the 0V reference was not the same across the panel. I had to fix this by bonding the 0V terminals of the power supplies together during the debug process. If I were to do this again, I would wire each power supply to the terminal strip and bond all the 0V signals to ground.
- Due to the lack of a safety controller, I wired the safety outputs of the light curtains to the PLC to act as the safety controller for lab demonstrations. I didn't realize that these signals are actually very fast pulsing signals that the PLC will catch in a tripped state every so many scan times. This caused the robot to fault randomly during testing. If I were to do this again I would have designed around an actual safety controller or safety input module.
- When I originally started the project I had planned to control all welding parameters from the HMI. Although as I got into the system I realized that FANUC does not allow the indirect referencing of weld schedule parameters. If I were do to this again I would have filled out multiple weld schedules and then allowed the HMI to choose the weld schedule that has the parameters desired.
- During the testing process I realized the proximity sensor signals became very noisy during the welding process. I then learned that the electromagnetic field and gas from welding can effect traditional sensors. If I were to design another welding cell, I would make sure to purchase weld grade sensors.

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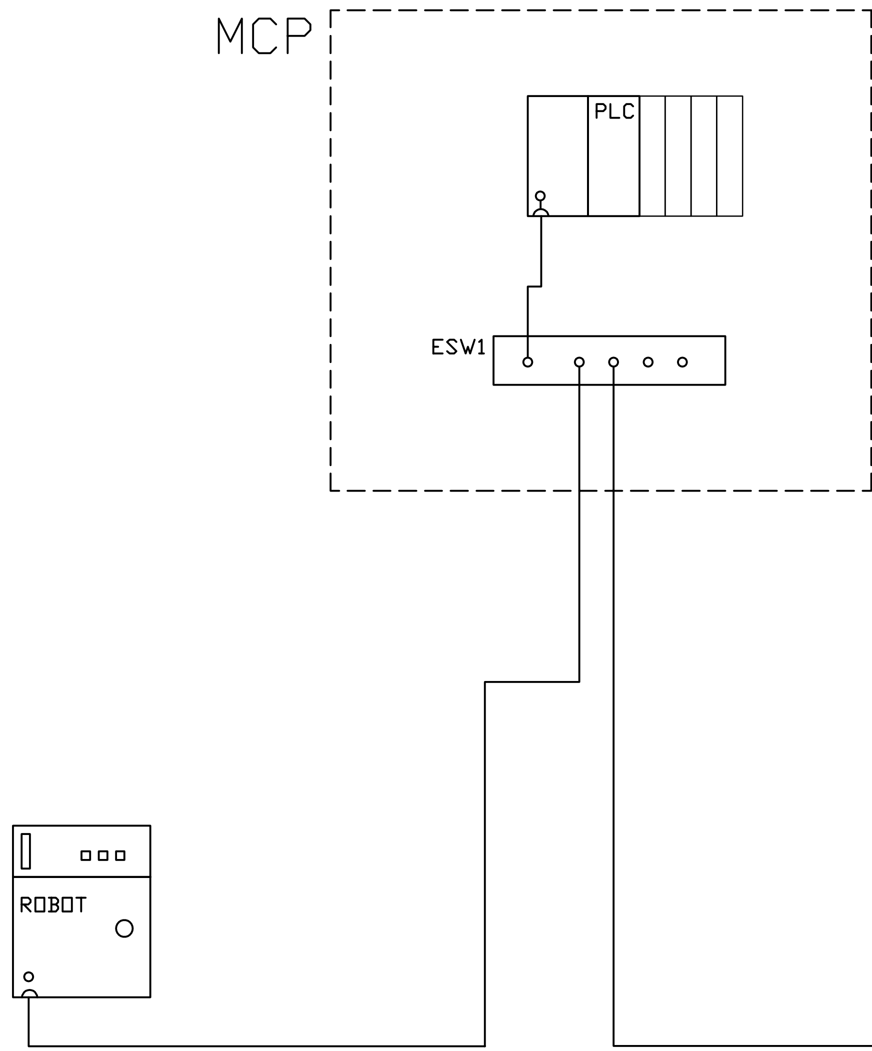
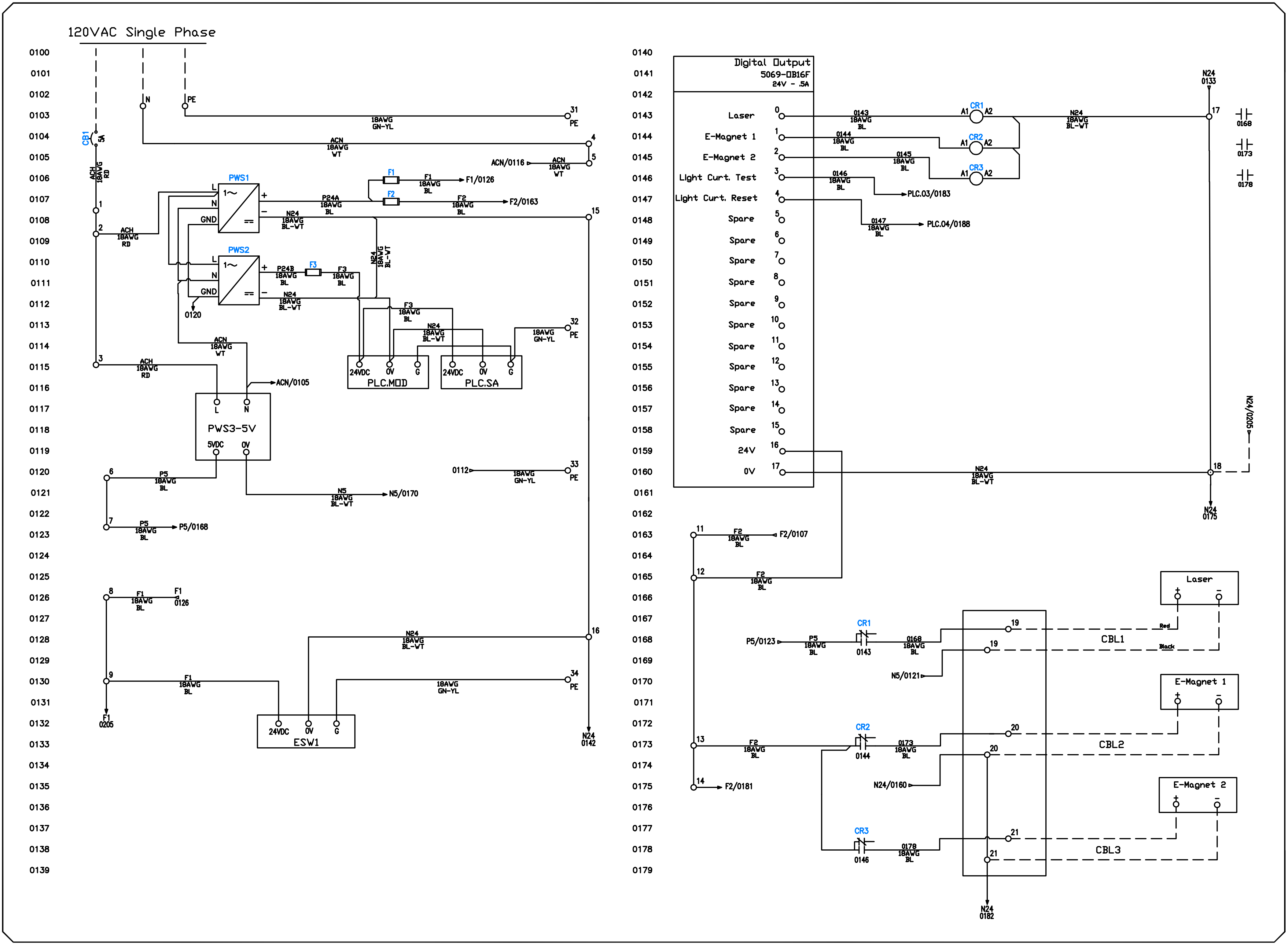
A Appendix A

(Schematics on following page)



Device	IP ADDRESS	SUBNET MASK
PLC	192.168.1.201	255.255.255.0
HMI	192.168.1.211	255.255.255.0
ROBOT	192.168.1.221	255.255.255.0



120VAC Single Phase
CB1
5A
PWS1
PWS2
PWS3-5V
PLC.MOD
PLC.SA
ESW1
F1
F2
F3
Digital Output
5069-OB16F
24V - .5A
Laser
E-Magnet 1
E-Magnet 2
Light Curt. Test
Light Curt. Reset
Spare
24V
0V
CR1
CR2
CR3
CBL1
CBL2
CBL3
Red
Black
F1/0126
F2/0163
ACN/0116
ACN/0105
N5/0170
P5/0168
F1/0205
N24/0142
PLC.03/0183
PLC.04/0188
N24/0133
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P5/0123
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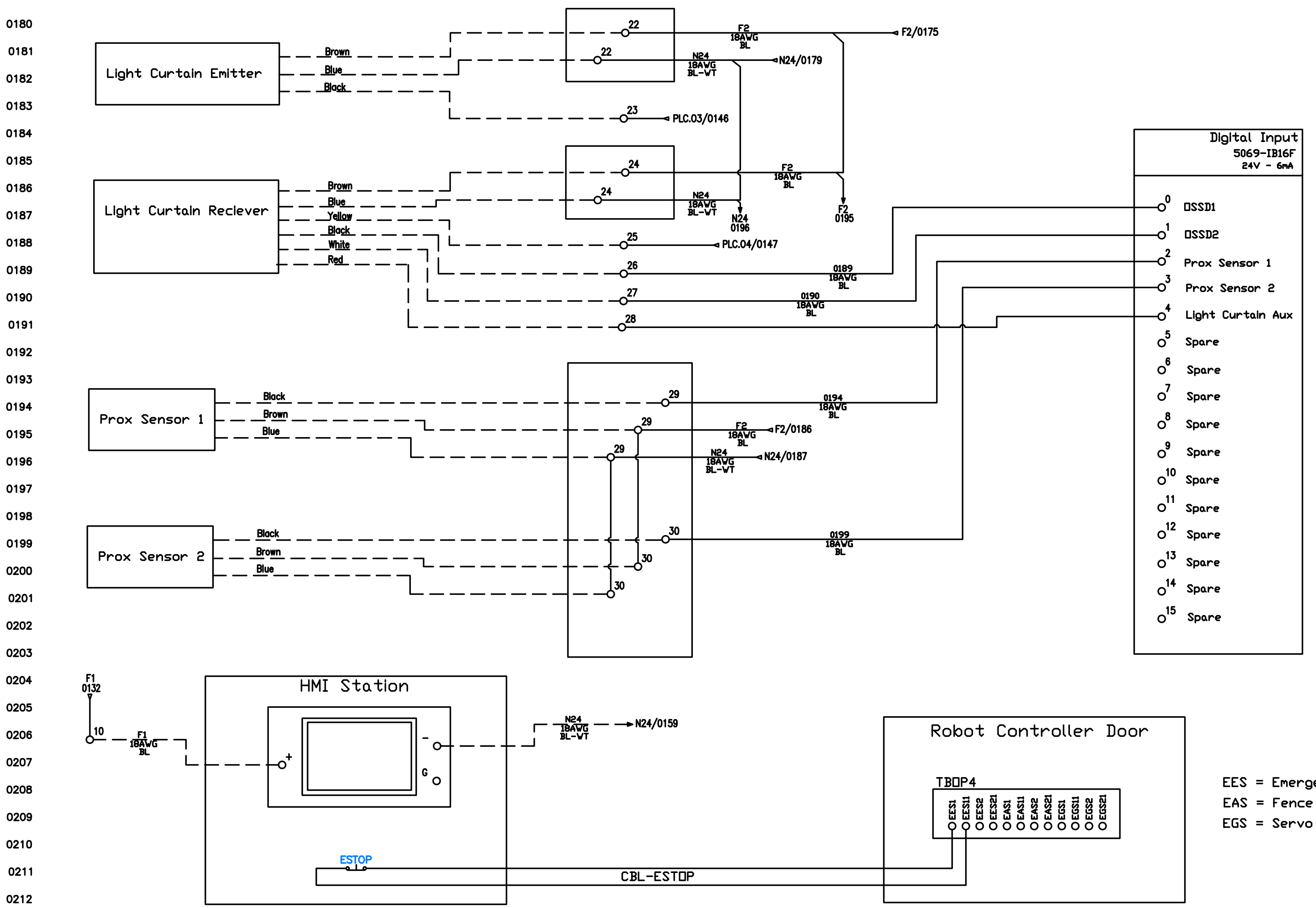
N24/0160
F2/0181
N24/0182



Use cable to bring power to HMI station labeled 'CBL-HMI'
Run the Estop cable through control panel and to HMI station

EES = Emergency Stop
EAS = Fence
EGS = Servo on/off input switch

B Appendix B

Mechanical Design BOM						
P/N	Description	Qty	Vendor	Notes	Unit Cost	Total Cost
15213	6061 Aluminum Bar (1.25" x 3.5" x 12")	1	OnlineMetals	Fixture Material	$48.42	$48.42
91075A199	Male-Female Threaded Hex Standoff	4	McMaster		$11.25	$45.00
92196A535	1/4-20 Socket Head Screw	1	McMaster	Mount Fixture	$19.67	$19.67
5698K212	DC Electromagnet	2	McMaster		$57.50	$115.00
PEW2-AP-4F	Inductive Proximity Sensor	2	Automation Direct	5mm sensing distance	$32.00	$64.00
92314A830	10-32 Hex Head Screw	1	McMaster	Magnet Mounting	$11.03	$11.03
0618-BC	Wheeled Lectern with Storage Shelf	1	Amazon	HMI Podium	$130.00	$130.00
47065T102	1.5" T-Slotted Framing	4	McMaster	6' Length	$46.50	$186.00
5537T51	Closed Gusset Bracket	8	McMaster		$9.82	$78.56
8605N26	M8 Cable	2	McMaster	32.5' Length	$50.92	$101.84
298-15857-ND	Adhesive Zip Tie Holder	25	Digikey		$1.79	$44.73
7130K12	Zip Ties	1	McMaster	Pack of 100	$3.53	$3.53
80005K11	Zip Ties	1	McMaster	Pack of 100	$8.00	$8.00
3136N401	T-Slot Framing Nuts	20	McMaster		$3.25	$65.00
7432K76	Spiral Cable Sleeving	1	McMaster	3/16" ID (25')	$23.20	$23.20
7432K77	Spiral Cable Sleeving	1	McMaster	5/16" ID (25')	$37.97	$37.97
OxLasers	Red Laser Line	1	Amazon		$39.00	$39.00
RJ45 Coupler	Ethernet Cable Extender	1	Amazon	Pack of 6	$11.49	$11.49

Electrical Design BOM						
P/N	Description	Qty	Vendor	Notes	Unit Cost	Total Cost
N412242410WC	Wiegmann Ultimate Series Enclosure	1	Automation Direct	24x24x10"	$641.00	$641.00
NP2424C	Wiegmann Subpanel - white	1	Automation Direct	White	$83.00	$83.00
KPR-SCE-24VACDC-1	Relay	3	Automation Direct		$6.75	$20.25
PSL-05-010	5V Converter	1	Automation Direct		$31.00	$31.00
DN-R35S1-2	Din Rail	1	Automation Direct	2m Length	$12.50	$12.50
T1E-2222G-1	2in Wire Duct	1	Automation Direct	6.5ft Length	$24.50	$24.50
T1E-1022G-1	1in Wire Duct	1	Automation Direct	6.5ft Length	$21.00	$21.00
GCX3141	E-Stop Button	1	Automation Direct		$15.50	$15.50
PSM24-090S	Rhino Power Supply	1	Automation Direct		$113.00	$113.00
DN-F10MN	Fuse Block	1	Automation Direct	Pack of 10	$33.00	$33.00
3044076	Terminal Block	35	Allied Electronics	UT25	$1.64	$57.40
3044092	Terminal Block	10	Allied Electronics	UT25PE	$5.05	$50.50
3044128	Terminal Block	2	Allied Electronics	UT4PE	$6.11	$12.22
3044102	Terminal Block	2	Allied Electronics	UT4	$1.57	$3.14
3044636	Double Level Terminal Block	8	Allied Electronics	UTTB 2.5	$5.35	$42.80
3214259	Triple Level Terminal Block	5	Allied Electronics	UT 2 5-3L	$6.97	$34.85
KN-EB4-10	End Blocks	2	Automation Direct	Pack of 10	$3.50	$7.00
2907562	Phoenix Contact 5A Circuit Breaker	1	Allied Electronics		$21.99	$21.99
3030174	Phoenix Contact 3 Pole Jumper	4	Allied Electronics		$1.63	$6.52
3030161	Phoenix Contact 2 Pole Jumper	4	Allied Electronics		$0.85	$3.40
GMA2	2A Fuse	1	Automation Direct	Pack of 5	$5.75	$5.75
GMA3	3A Fuse	1	Automation Direct	Pack of 5	$5.75	$5.75
Q0170-1	18 AWG Cable	250	Automation Direct	Measured by the foot	$0.41	$102.50
C5E-STPBL-S25	25 ft Ethernet Cable	1	Automation Direct		$22.00	$22.00
BRM14-2	Cable Entry Plate	1	Automation Direct	14 5-11mm openings	$19.00	$19.00
1300550001	RJ45 Bulkhead	1	Digikey		$45.67	$45.67
3214314	3 Level Block End Cover	5	Allied Electronics		$1.57	$7.85
3047293	2 Level Block End Cover	5	Allied Electronics		$1.52	$7.60
7082K22	16AWG Power Cable	10	McMaster	10ft Length	$1.07	$10.70
9096T11	3-Blade Straight Plug	1	McMaster		$16.85	$16.85
M21-500-595-WT	Vinyl Labels	1	Allied Electronics	Wire Labels	$25.48	$25.48
2907487	Circuit Breaker	1	Allied Electronics		$25.20	$25.20
7243K11	Female Quick Disconnect Crimp	1	McMaster	Pack of 50 (22-18 AWG)	$21.84	$21.84
7243K12	Male Quick Disconnect Crimp	1	McMaster	Pack of 50 (22-18 AWG)	$23.69	$23.69

Total Cost	$2,606.89

Figure 67: Project Bill of Materials