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REMOTELY CONTROLLED INDUSTRIAL ROBOTIC ARM
AND SIMULATION OF AUTOMATED THERMAL FURNACE

By
Prince K. Mehandi Ratta

A REPORT

Submitted in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE

In Mechanical Engineering

MICHIGAN TECHNOLOGICAL UNIVERSITY
2019

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This report has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Mechanical Engineering.

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Abstract

The right execution of controllers ensures the correct analysis of information, generating efficient results and better optimizing the system. In this report, two controllers were designed. Firstly, a remotely controlled robotic arm, since there are no such type commercially available controllers. Moreover, robotic platforms are costly, so students and researchers are often unable to learn the concepts of programming industrial robots. This project makes a non-destructive, remotely-controlled robotic arm to better teach students and researchers about programming and control of robotic arms. Secondly, simulation of an automated thermal furnace for ArcelorMittal on SIMULINK, which is used for the annealing process of steel strip. The annealing process requires heating and cooling of the strip within a short duration to make metals more workable and to improve the ductility, resistance and hardness. The proposed simulation project for ArcelorMittal is used to virtually demonstrate the annealing process of a furnace.

1. Introduction

The robotics market is growing rapidly and globally. An article published in 2018 by the International Federation of Robotics¹ on World Robotics sales, shows a 30 percent increase in sales in year 2017 compared to 2016. This amounts to 381,000 more robots sold globally. With the apparent demand of industrial robots, there is a need for more trained robotic specialists. Even though robotic simulation software is available online, virtual robots are hard to understand or control for many people. This project applies a new concept with the available virtual robot technology to make a non-destructive, remotely-controlled robotic arm to better teach students and researchers about programming and control of a robotic arm. Since there are no commercially available remotely controlled robotic arms, and because of the high cost of robotic arms, students and researchers are often unable to test their programs on real robots. By applying the following concept of a remotely-controlled robotic arm, universities already equipped with industrial robots can share existing resources with other universities to teach programming of industrial robots. Using this developed system, to allow remote access to the physical robot, interested parties can test their programs on a real robotic arm instead of simply working in robotic simulation environments.

To achieve this goal, a three-part system has been designed i.e., the hardware to control the teach pendant of a physical robot, a system that captures and transmits video, and a website used by the client to remotely access, control, and program an industrial robotic arm. To gain remote access to the robot, the client requests a login token for the specific access time and access duration to the robot. Upon receiving approval from an administrator, the user is provided with a teach pendant control web link, which is limited to only the pre-approved time slot. The interface for the client consists of the virtual teach pendant, a display of the real teach pendant screen and two display screens showing the robot from different angles. The system layout designed, in Figure 1, shows three cameras in total for the system, where two cameras are placed in order to stream the live feed of the robot's movement and a third camera shows the display of the teach pendant on the website, which will be further discussed.

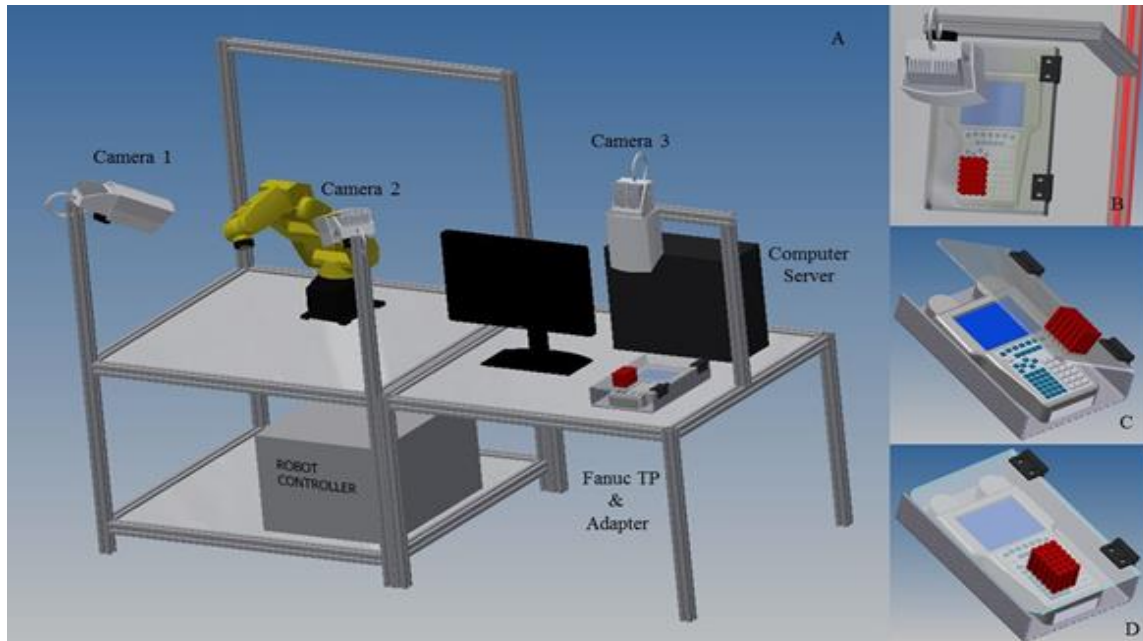


Figure 1: (A) Robot remote system proposed model with two-live camera feed of the robot, (B) Top view of the teach pendant camera set up, (C) and (D) The initial testing phase of teach pendant with the push buttons

When the client presses any input on the virtual teach pendant, the data are transmitted via the internet to the arm server, which, using Modbus TCP/IP to communicate with a programmable logic controller (PLC), activates the hardware to control the teach pendant which is shown in Figure 5. The vision system implements the digital camera, mounted above the real teach pendant's display to capture and feed real-time data. The video signals captured by the vision system from the real teach pendant, as well as from the physical robot, are transmitted to the vision system server. This sends the video stream to the client, enabling the user to observe the real-time teach pendant display and motion of the robotic arm.

For an example, if the user presses the buttons on the virtual teach pendant, to jog the robot in X axis, then camera will show the robot's movement in X axis. This enables remote access for users wishing to learn robotic programming concepts. While robotic simulation software can be used to achieve this, the solution described here provides an actual interactivity with the physical system, allowing the user to interact with the robotic arm and learn or test the programming skills used in industrial robots. For an example, the researcher made an entire program on the virtual software to do the welding of the robot but wants to do the dry run on the real robot before implementing it into an actual running system, this system will allow the user to test their program.

2. Background on the existing remote robot platform

The medical sector has applied similar concepts, for example, using a remote robot-assisted laparoscopic cholecystectomy on a woman with a history of abdominal pain and cholelithiasis.² The surgery was done successfully across transoceanic distances with the surgeons being in New York and the patient located in Strasbourg, France. Therefore, a similar concept can be implemented in academia to provide students and researchers an opportunity to gain hands-on experience operating industrial robotic arms.

As manufacturers are moving towards automation-based assembly or production lines, industry and academia must join forces to prepare for today's manufacturing demands. The developed complementary Robot Run, robotic simulation software at Michigan Tech³ provides a free education simulation tool to students to learn programming concepts. The developed simulation environment has been used by many institutions to teach students the concepts of industrial robotics.

3. Description of Robot Remote

To control the robot at the Industrial Automation lab of Michigan Tech, equipped with FANUC LR-Mate 200iC robots, the hardware is designed to control the robot's motion without damaging any buttons of the teach pendant. The push-type actuators, controlled by the programmable logic controller (PLC), enable activation of the individual keys on the teach pendant to generate the motion to enter programming instructions, while designing the robotic program. Figure 2 depicts the overall layout of the remote robot system. The robot is a machine and if the programmer keeps jogging the robot to the maximum extent, it will break the glass walls around it. The glass walls are there to protect the programmer or operator because if something breaks, it can be risky to human body. In order to ensure the safety, of the robot and glass enclosure, the robot's collision guard feature which provides sensitivity to detect that the robot has collided with an object and then stops the robot immediately. The system developed follows all the security norms in order to provide the secured communication⁴ between the remote robot system and the operator using the client's website.

In case of internet connection lost at either of the sides or if the website crashes, the PLC disconnects from the website immediately and all of the actuators will not operate until the secured and stable communication is achieved. The flow chart of the remote robot system's website development is shown in Figure 3 and the PLC and computer connected runs on MODBUS/TCP protocol. To explain web security, HTTPS requests two items: Certificate (Authority) or TLS (where Certificate does the IP address verification and then the client

server requests for authentication), and TLS, which does the encryption data process to transmit the data between sender and receivers in an encrypted form. Since this is an encrypted process, the potential attacker doesn't have the access to decrypt the data, resulting in the data being transmitted securely as it utilizes public key cryptography (PKC) or asymmetric key algorithm (an encryption technique).⁴



Figure 2: The final setup of remote robot system with FANUC LR-Mate 200iC robot and CLICK PLC

The Industrial Automation lab of Michigan Tech in EERC has 4 FANUC LrMate 200iC Robots. To make this experiment work, one robot and its teach pendant is used. The hardware is designed in such a way that the teach pendant can be removed from the enclosure for lab experiments and can be attached to the enclosure at the time of utilizing the project.

The cybersecurity of industrial controls systems is almost mandated to have the security protocols to protect the systems from hacking. The communication protocol used between the PLC and the connected computer is Modbus/TCP. The PLC programming is done in such a way that if there's no input provided for 4 seconds, then the CLICK PLC will not provide the output signal to the actuators. Also, communication verification will be

required or refreshed in order to ensure the safety check. Moreover, Hypertext Transfer Protocol Secure (HTTPS) is encrypted using transport layer security which provides the secured web-based controlling of the robot, Figure 3 shows the flow of the signal.

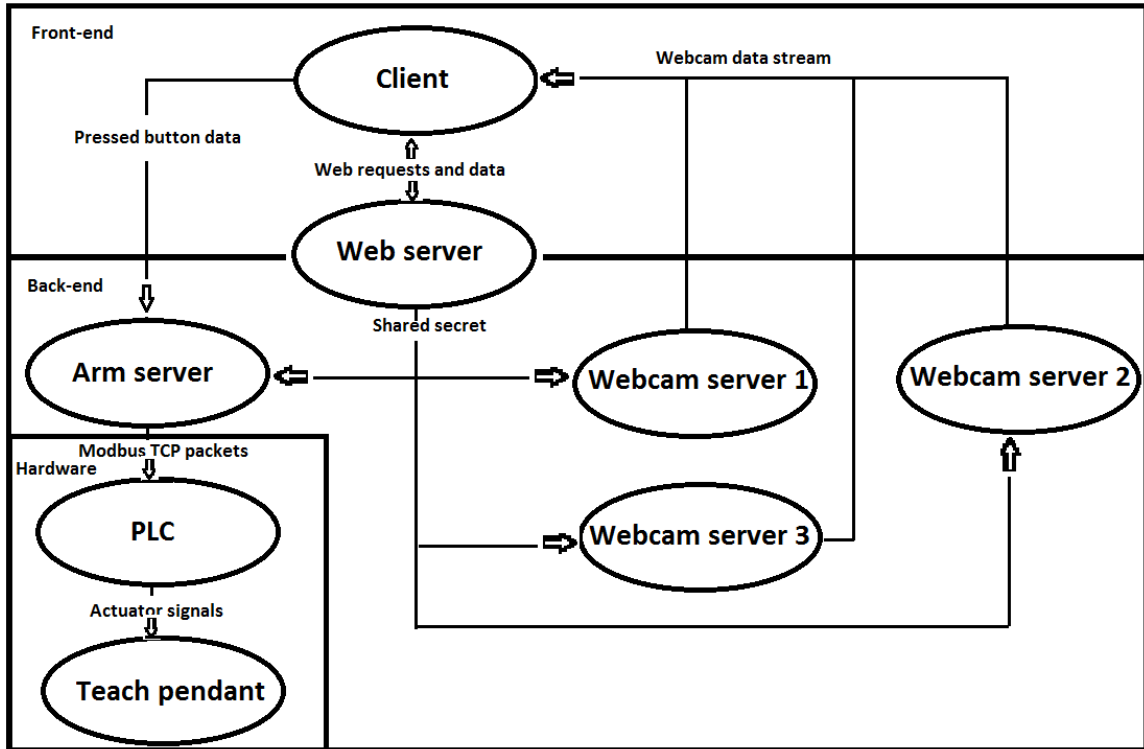


Figure 3: The flowchart of the backend programming for the remote robot system's web interface

3.1 System Design and Solidworks Model

The system layout shown in Figure 4, provides a big picture of the entire working system. There is an operator at the right who has access to the robot via the designed website. The computer (B) needs to have internet in order to communicate with the computer (A) at the other end of the system. The computer (A) is connected to the PLC, the webcam and to the internet. The data or virtual buttons pressed signal on the website from computer (B) is coming to the computer (A) over internet. The signals are then sent to the PLC via Modbus communication protocol. The PLC is connected with all the actuators which are pressing the buttons on the teach pendant. The actuators are placed on the designed enclosure and the Solidworks design of that enclosure will be shown in Figure 5. Also, another webcam is connected on the ceiling of the enclosure in order to stream the live display of the teach pendant.

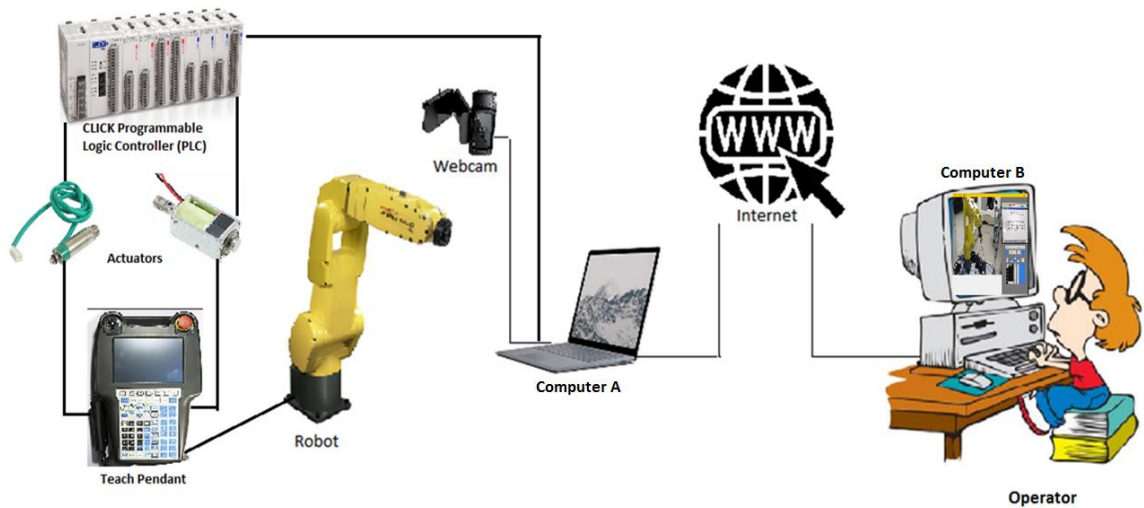


Figure 4: Developed System layout of the entire setup in the lab for running the Remote Robot designed in paint software by using the pictures of the products used in order to make this project work

Designed in Solidworks, the remote robot system is dedicated to the teach pendant of FANUC LR Mate 200iC after analyzing the distance between each key. The frame to support the teach pendant has a bottom plate, a middle plate and a top enclosure plate. The teach pendant is kept between the bottom and the middle plate. The bottom plate holds the teach pendant, designed by using readily available screw holes on the back of the teach pendant. Four rods, shown by #1 in Figure 5 were attached to the plate to hold the teach pendant in place which are also shown in Appendix A.

The middle plate is designed with circular openings to secure the actuators. To activate the robot motion, the “Shift” key and “Deadman” three-way switch must be continuously pressed on the teach pendant. To achieve this, the latching type actuators were selected. The designed model is shown from various angles in Figure 5. Moreover, in order to press the “Deadman” switch using the latching actuator, the designed mounting plate, shown by #2 in Figure 5, is also added to the bottom plate. Appendix A also shows the way of mounting the actuators on the middle plate.

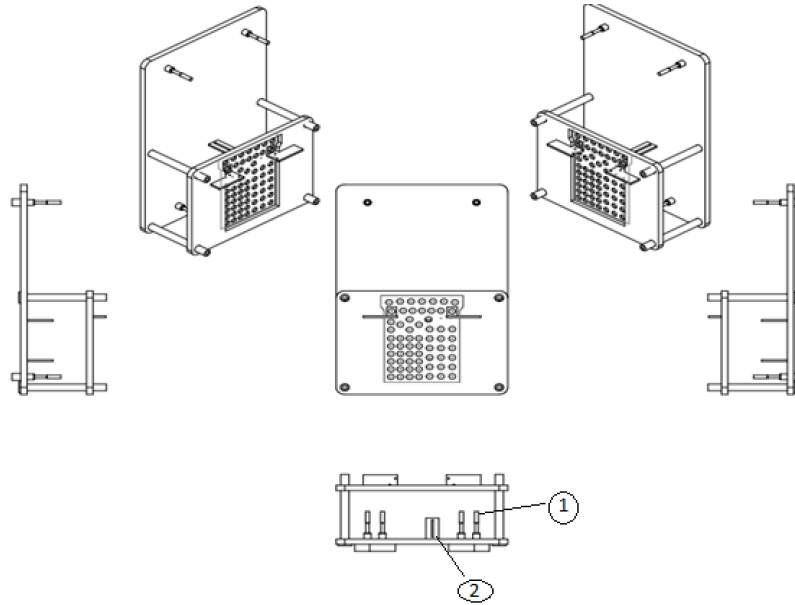


Figure 5: Solidworks model of the remote robot setup for the initial system without camera attached for the teach pendant display

The top enclosure plate is designed for the webcam mounting, which shows the display of the teach pendant to the user. The top plate also acts as a protective cover for the teach pendant screen and reduces the amount of light falling on the screen of the teach pendant to reduce glare and therefore provide better video quality to the client viewing the teach pendant screen. The outer layer of the top plate is used for mounting the DIN rails, “Click” PLC, relays, wiring cable duct, two power supplies and the inner layer for terminal blocks on DIN rail. Moreover, in order to provide the protection to the operator, all the wiring is enclosed behind the glass casing.

3.2 Components description

The remote robot system components were selected after considering the area limitations of the teach pendant and appropriate weight required to press the keys of about 370 gram at 0.5 mm stroke length and not harm them or the “Deadman” switch but to still provide reliable operation over an extended period. The three latching type actuators were in parallel connection to drive enough current needed to apply necessary force through the relay mechanism to the “Shift” key and “Deadman” switch. It is calculated that 0.77A of current is suitable for the application considering the operating losses and by testing it at several current values in the lab. The specifications of all the components used for the remote robot system are shown in Table 1.

Table 1. Description of components of the remote robot system

Component	Description
Programmable Logic Controller	Model: C0-10DD1E-D with MODBUS/TCP, which is provided by Automation Direct website.
CLICK Power Supply	Model: C0-01AC for CLICK PLC, which is provided by Automation Direct website.
8 Output Modules	Model: C0-08TR with 1 Ampere/point, which is provided by Automation Direct website.
2 Power Supply	Model: MEAN WELL MDR-60-12 AC and MDR-60-24 AC
61 Push Type Actuator	Model: 9SIA27C3KH1422. It operates at DC 12V 0.77A and is manufactured by Unique Bargains and provided by Newegg, which is used for all the keys other than Deadman switch and Shift key.
3 Latching Type Actuator	Model: DSMS-0730-24. It operates at DC 24V 0.16A each and is provided by Digi Key, which is used for Deadman Switch and Shift Key.
4 Din Rails	Model: D357A11-305. In order to mount the PLC, terminal blocks and Relays, purchased from Amazon.
Relays	Model: 781-1C-24D, 781-1C-SKT. 1 OMRON Relay and 2 Automation Direct Relays.
100 Terminal blocks	Model: ER-039. To connect the wires of the actuators with the PLC outputs, purchased from Amazon.
1 Wiring cable duct	Model: AD105X1. To do the wiring in a professional way, purchased from Amazon.
100 Cable Ties	Model: TR88302. It was used in order to bundle all the actuator wires in a professional manner, purchased from Amazon.
Terminal Block Press-Fit Jumper	Model: B07HMY1B4P. It was bought from Amazon and was required to short the terminal blocks where one input signal was used to provide the supply to many actuators

3.3 System Integration

The remote robot system setup is shown in Figure 6. Figure 6 (left) demonstrates front view of the hardware setup and consists of CLICK PLC, power supplies and relays. The inside view, provided in Figure 6 (right), shows all the solenoids controlling teach pendant keys and wiring approach with implementation of the terminal blocks. The description of all the PLC output connections with all the teach pendant keys via actuators on middle plate is shown in Table 2, with a photograph in Appendix A.

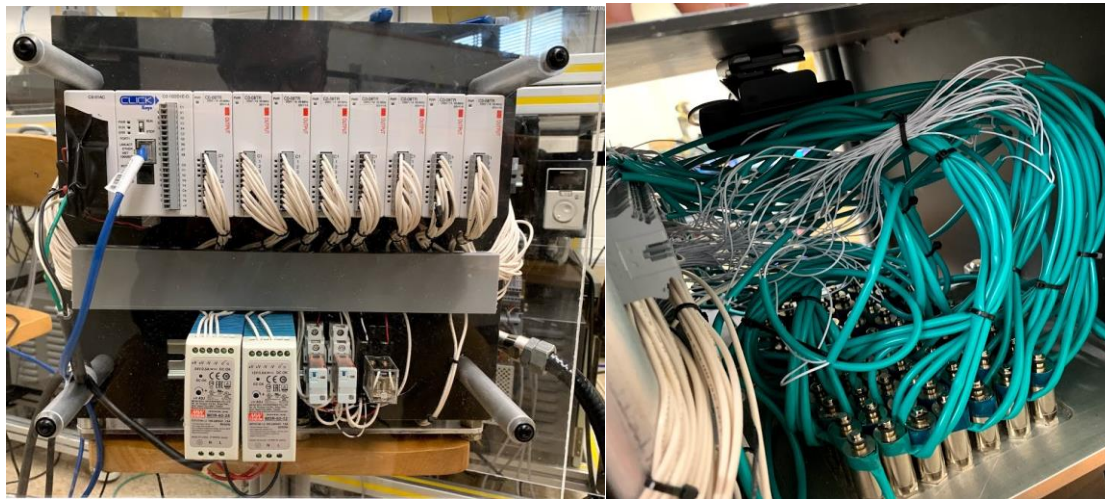


Figure 6: (left) The outer layer of remote robot which consists of CLICK PLC, Din Rail and its cover, 2 Power Supplies, 3 Relays and a sheet of glass to provide the protection, (right) The inner layer of the remote robot which shows all the actuators attached and wired up to the terminal blocks on the left which is connected to the PLC with white wires as shown and a camera attached on the ceiling

The PLC output modules⁶ are the sinking type, which requires connecting the negative output of the power supply to the common of the PLC output modules, as shown in Figure 7. Therefore, for the push type actuators requiring 12V, 0.77A supply, one end of each actuator is connected to the PLC outputs and the other end directly to the positives of the power supply. Table 2 provides the terminal block assignment with the respective actuators. To connect all the ‘positive ends’ of the actuators, the terminal block jumper is used to provide the ‘positive ends’ 12V, 0.77A to all those terminal blocks where ‘positive ends’ of the actuators were connected. Figure 7 shows an example of the wiring approach of one actuator used to control a teach pendant key. An output point of the PLC (Y801 of C0-08TR) is connected to the negative terminal of the actuator and the positive terminal of the actuator is connected directly to the positive of the power supply #3 shown in Figure 7. Similarly, all the other actuators were connected to the PLC. However, Y101-104 were connected to ‘negative ends’ of 24V, 0.77A and the output terminals (Y101-103) of the

PLC were connected to relays A1, A2 and B as shown in Figure 7. A figure of the teach pendant is shown in Appendix A.

Table 2: A table to address the PLC Outputs with Teach Pendant Key and MODBUS address

PLC Output	Teach Pendant Key	MODBUS Address	PLC Output	Teach Pendant Key	MODBUS Address
Y101	PRESS(SHIFT+DEADMAN)	16384	Y501	9	8352
Y102	RELEASE(SHIFT+DEADMAN)	16384	Y502	6	8353
Y103	RELEASE(SHIFT+DEADMAN)	16384	Y503	ITEM	8354
Y104	N/A	N/A	Y504	, -	8355
Y105	GROUP	8288	Y505	POSN	8356
Y106	F5	8229	Y506	3	8357
Y107	NEXT	8230	Y507	PREV	8358
Y108	DISP	8231	Y508	.	8359
Y201	+Y(J2)	8256	Y601	5	8384
Y202	-ZR(J6)	8257	Y602	2	8385
Y203	+XR(J4)	8258	Y603	7	8386
Y204	+Z(J3)	8259	Y604	4	8387
Y205	+ZR(J6)	8260	Y605	8	8388
Y206	+YR(J5)	8261	Y606	BACKSPACE	8389
Y207	+X(J1)	8262	Y607	1	8390
Y208	-YR(J5)	8263	Y608	0	8391
Y301	-X(J1)	8288	Y701	MENU	8416
Y302	-XR(J4)	8289	Y702	UP ARROW	8417
Y303	-%	8290	Y703	SELECT	8418
Y304	+%	8291	Y704	LEFT ARROW	8419
Y305	COORD	8292	Y705	RIGHT ARROW	8420
Y306	-Y(J2)	8293	Y706	DOWN ARROW	8421
Y307	-Z(J3)	8294	Y707	STEP	4822
Y308	BWD	8295	Y708	RESET	8423
Y401	HOLD	8320	Y801	F2	8448
Y402	STATUS	8321	Y802	DATA	8449
Y403	SETUP	8322	Y803	FCTN	8450
Y404	FWD	8323	Y804	F3	8451
Y405	TOOL 2	8324	Y805	F4	8452
Y406	MOVE MENU	8325	Y806	EDIT	8453
Y407	ENTER	8326	Y807	I/O	8454
Y408	TOOL 1	8327	Y808	F1	8455

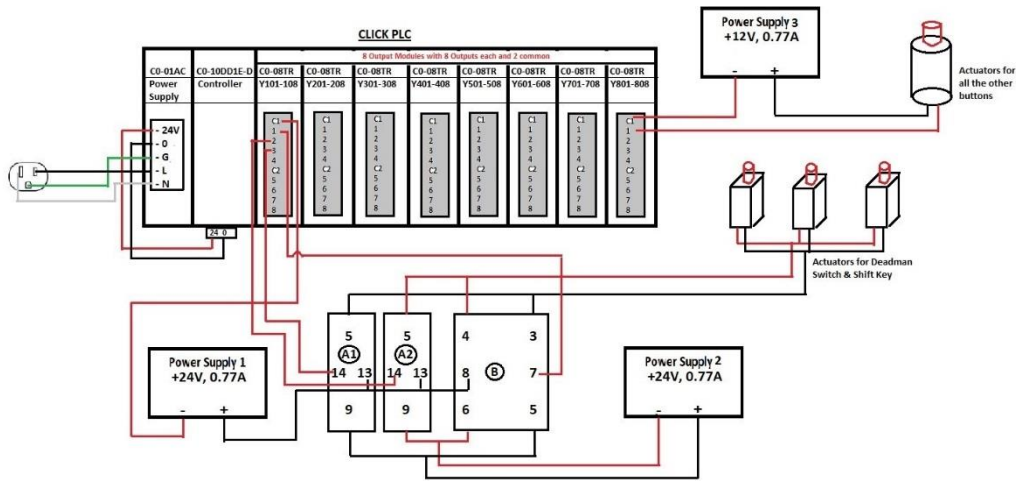


Figure 7: The wiring schematic for the entire system which shows the CLICK PLC, 3 latching type cuboid shaped actuators connected to 2 Power supplies and 1 cylindrical actuator, which represent all the push type actuators connected for all the buttons on teach pendant

The latching type solenoids, shown in Figure 7, are connected to the relays A1, A2 and B, required actuation to simulate the operator pressing and holding the “Shift” key and “Deadman” Switch. Therefore, for jogging the robot virtually (movement of robot in the respective axis to which it is commanded to using the teach pendant keys), the operator needs to press the “Shift” key once on the simulated teach pendant, and the controller will actuate the latching mechanism. Similar operation actuates the “Deadman” switch. Pressing again either “Shift” key or “Deadman” switch will release the latching mechanism and the physical components of the teach pendant will be disengaged.

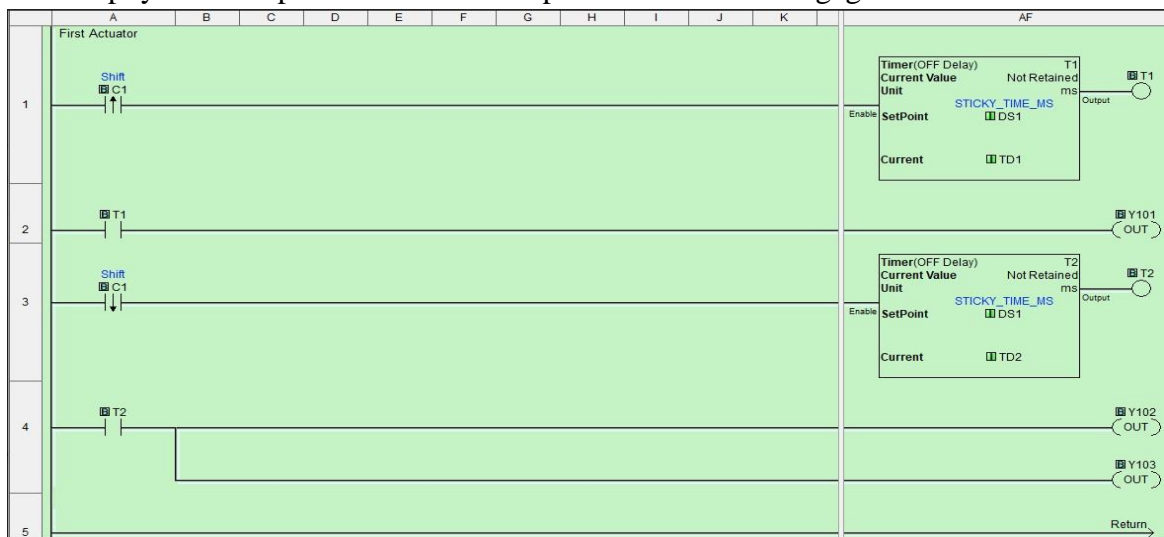


Figure 8: PLC code to press and release of “Shift” Key and “Deadman” Switch using rising and falling edge inputs of PLC program and Off Delay Timers

Generally, latching type actuators extend in one direction, and even when power is removed it remains in the extended position. To retract it, the pulse of reversed polarity is required. Relay B in Figure 7 provides the main condition with the extended operation supply for the actuators, and to reverse the polarity of the actuators, the relays A1 and A2 were used. Three power supplies were required: two power supplies with 24V with 0.77A and one with 12V with 0.77A power supply, as shown in Figure 7.

The PLC programs, shown in Figure 8 and 9, controls the “Deadman” switch. The “Shift” key uses “Timer off” instruction to delay the rung or that line of code. Moreover, if the signal breaks or the computer server gets disconnected, the actuators require a reset function. Figure 8 shows the PLC code, which ensures the reset capabilities of the actuators used for the “Deadman” switch and “Shift” key. To ensure the system’s safety, the controlling program resets the signal after the signal has been absent for four seconds.



Figure 9: Security of SHIFT and Deadman Switch by using Reset All block for resetting the system if servers are disconnected for 4 seconds

4. Signal Flow

The user-friendly website, designed to control the robot, contains the required information needed to operator the robot as shown in the Figure 10. To maintain a secure system, access to the control panel is only provided to one computer/user at a time with approved login credentials. If the control panel is to open on any additional device, the program generates an error in loading the control panel page, as this could signal a security breach, posing a risk for the robot operation or for the operator’s work. The website, is currently on private domain but on release, will be functional via <https://pages.mtu.edu/~kuhl/robotics/>

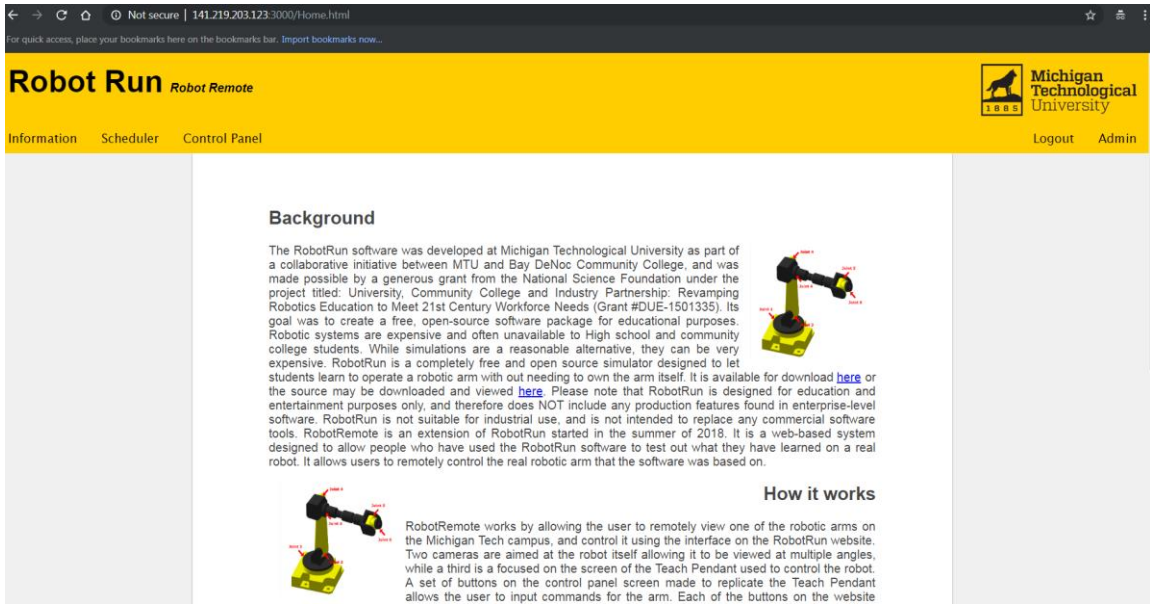


Figure 10: Robot Run (Robot Remote) web page showing the front page and the documentation for the project operation

The website is currently operated through a web link assigned to Michigan Tech’s specific http address, which can be loaded only when the computer is connected to the PLC and the computer has access to the internet. The client needs to access the designated project website, select the time slot, and receive an approval from the administrator. The robot is tested out for proper operation before giving full access to the client. Once the full access is granted, the user has full control of the robotic arm that can be controlled using the teach pendant displayed on the screen. The two cameras provide real-time feed streaming the video of the robot and displaying the screen of the actual teach pendant, as shown in Figure 11.

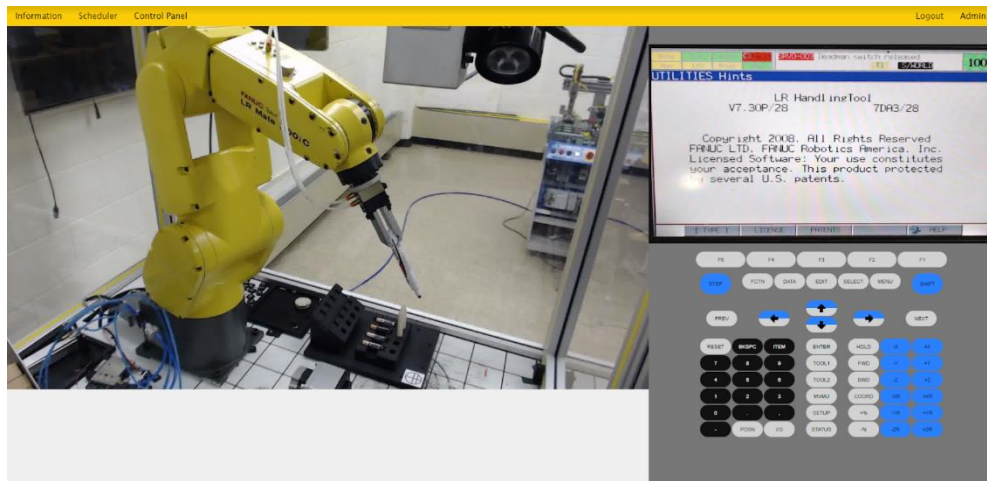


Figure 11: Client’s view screenshot of the Control Panel, of a FANUC robot in the left via 1st camera and 2nd camera for teach pendant display as shown above the buttons on the right.

The website and the user interface for the website are designed after considering the FANUC proprietary and copyrights of the teach pendant. Neither the remote robot or Robot Run were designed to copy any of FANUC HandlingPro software. The project's motive is simply to help people learn more about the FANUC Robotics so they can visualize and practice, even if they lack expensive software or physical access to a robot.

5. Result and future work

The Remote Robot hardware and software have been tested to ensure its full functionality. It has also been pilot tested by a few undergraduate students at Michigan Tech. The students found the project very interesting and easy to learn by jogging the real robot instead of just jogging a virtual robot. The most important thing about the project is that they see the real time display of the teach pendant which also helped them learn the actual FANUC robot programming skills. The full utilization of the Remote Robot is underway by Dr. Aleksandr Sergeyev, and it is ready to be disseminated to users including students and researchers. With the help of the developed system, the users will be able to control the robot and develop their own scenarios through robot programs.

The research paper for this project has been published in ASEE's Pacific Southwest Section Meeting, 2019.⁷ The reviewers of the ASEE provided positive feedback on the project, "This robotic simulation appears to be a very valuable tool that allows students to test their programming remotely with industrial robots. It is an innovative approach and can be generative in terms of student learning outcomes" and "Very interesting and practical subject! I did not know that there is no commercially available remotely controlled robotic arm".

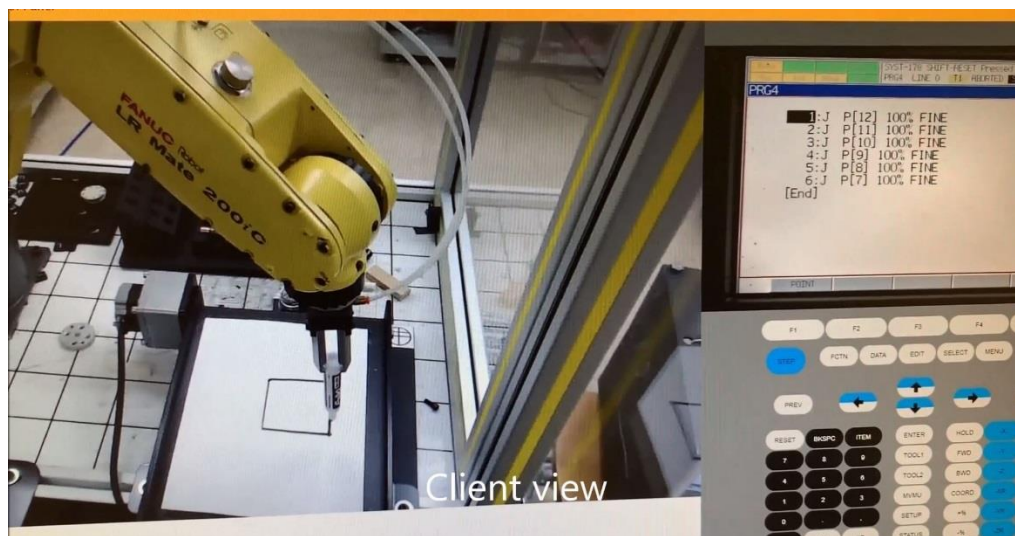


Figure 12: Client view of jogging the robot to draw a square

The project was tested with a few basic jogging and small program tests. A program of making a square was created on a piece of paper. A student jogged and saved the points on the page through Client view website as shown in Figure 12. The project ran successfully to draw the square as shown in Figure 13. For future work, the remote robot project will be extended to operation via tablet by developing the website and software options compatible for tablets and smart phones. Additionally, the visual feedback to the user can be enhanced by installing more cameras to provide multi-viewing angles of the robot.

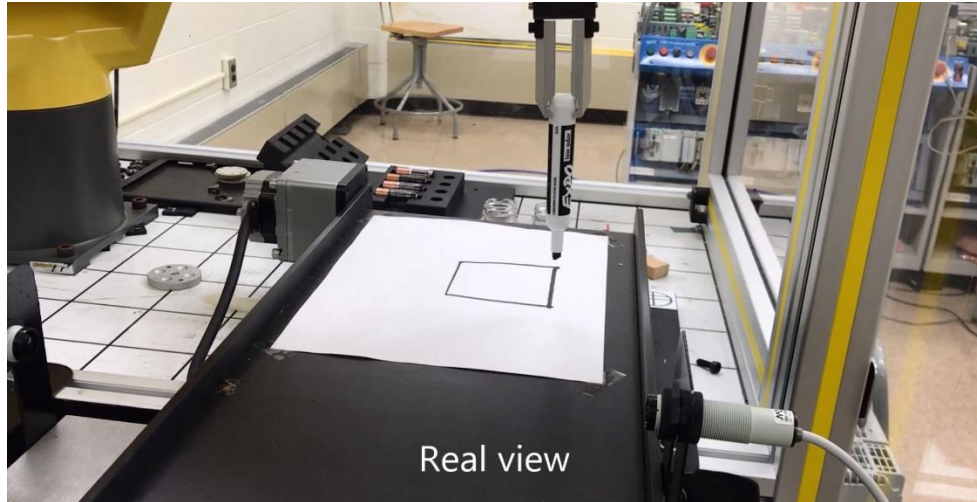


Figure 13: Real view of jogging the robot to draw a square

6. Simulation of Automated Thermal Furnace

The ArcelorMittal's main annealing thermal furnace control process heats a variety of steel sheets of different annealing codes, developed by ArcelorMittal, in order to bring them to a certain temperature for further processes. The process runs smoothly, without stopping the line entirely, using a loop car. The loop car moves back and forth to allow the line to stop relative to the welder and keep moving relative to the furnace. This process doesn't stop the movement of the steel strip in the furnace for an extended period, rather it keeps the movement continuous. Additionally, the new model prevents any section from overheating when a new strip is being welded.

The furnace is divided into three sections as a part of the annealing process; the preheat section, the radiant tube section, and the jet-cool section, as shown in Figure 14, provided by ArcelorMittal. The focus of the project is exclusively on the preheat and radiant tube section, where preheat consists of five zones while radiant consists of eight zones. The preheat furnace brings all the sheets to the minimum required temperature of 1200 F. For example, if all the sheets are operated at 1200 F or higher, then the preheat tunnel furnace is set at 1200 F in order to expedite the process for the radiant section. On the other hand,

the radiant section which has eight zones, is adjusted with several gas and air flow valves. They are modified by the operator in order to bring the sheet to the desired temperature.

At the end of each zone the temperature for a given zone is recorded by the thermocouple. Currently, the operator analyzes the obtained temperature data from the thermocouples and by controlling pyrometers. Then the operator does the adjustments to the heat control valves, which are used for increasing or decreasing the temperature of the zones.

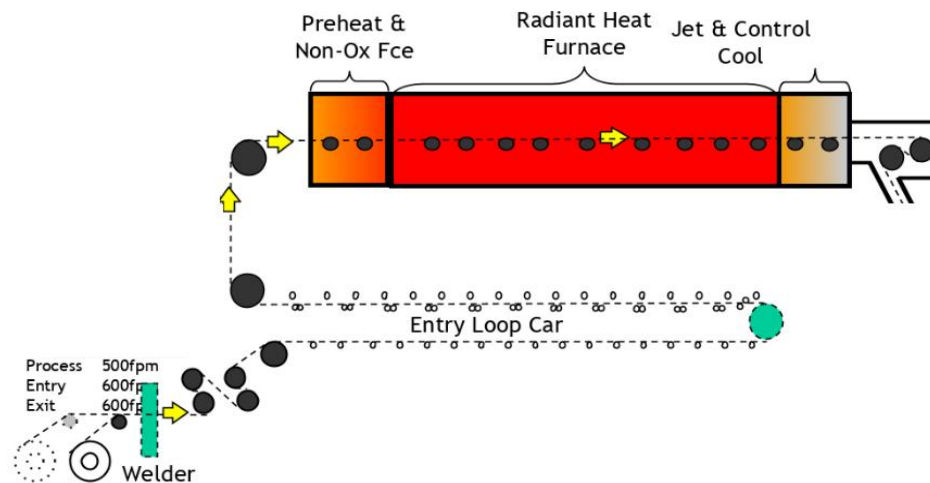


Figure 14: The flowchart, provided by ArcelorMittal, of the sheet through welder, Entry loop car, preheat and Non-ox Fce, Radiant Heat Furnace and Jet and Control Cool Section

However, in doing so, they lose some portion of the sheet which had not been brought to the desired temperature before exiting the furnace for the next step. If the strip is not within the desired range, that part of the strip is discarded. It leads to monetary losses and makes the process inefficient; thus, the system needs to be upgraded to make the furnace automated and to exclude the role of the operator and to plug the operator data automatically to the controller. Consequently, automating this process will eliminate human error and limit product losses as much as possible.

6.1 Background

ArcelorMittal is an Indian multinational steel manufacturing corporation headquartered in Luxembourg. It was formed in 2006 after the takeover and merger of Arcelor by Indian-owned Mittal Steel.⁸ Steel manufacturing companies around the world struggle with similar inefficiencies, and these companies strive to improve the efficiency of their process in order to set themselves apart from their competitors. However, regarding annealing furnaces, there are no set standards to achieve the best possible efficiency. This is because there are

differences in their layout, the method of heating, the shape of the materials that are to be heated, and the fuel that is used.

Xing and Chen designed a fuzzy feed-forward control system that was designed to regulate furnace temperature between the heating and soaking zones of the furnace.⁹ The furnace was having a difficult time regulating the temperature between these two zones because of the large temperature variation between them, and this was the reason for implementing fuzzy feed-forward control system. The term fuzzy refers to a control system that is not dealing with true digital output, and this is the case with valves that are controlling the fuel and air in the furnace which this paper referred to. This algorithm was integrated into the existing PLC program, and results showed that the temperature was significantly limited.

Attempting to design an intelligent temperature controller, three students from the School of Electronics and Information Engineering in Liaoning Province, China created a cascading temperature control system based on an adaptive neural fuzzy inference system (ANFIS). In their study, the fuzzy control system was designed to regulate the gas and air flow valves in the furnace. In order to test its functionality, a model was developed through Matlab and Simulink. The results of the simulation showed that the cascade control system the ANFIS intelligent control algorithm yielded excellent temperature control in comparison with other control systems.¹⁰

Predictive temperature control has also been proposed for annealing furnaces with a very similar process layout as ArcelorMittal.¹¹ (Hasegawa, 1994) designed a predictive control model that fetches future temperature values, and then changes the furnace setpoints preemptively in order to achieve the proper strip temperature upon exiting the furnace. In the process of ArcelorMittal's facility, the new strip is welded to the tail end of the previous strip. The furnace consists of a heating furnace and a cooling furnace, and these are divided into a series of zones where temperature can be controlled individually. Upon exiting the heating furnace, the strip must be within a specified temperature range. To create the predictive temperature control system, the engineers developed a mathematical model that combined strip data and furnace data to predict the furnace temperature as well as the strip temperature. When implemented, the model reduced the magnitude of error in strip temperature by two-thirds.

6.2 Model Design

The first step, before making any changes to the PLC program, was to design a simulation model of the current logic of the thermal furnace and run the entire furnace of that simulation model. It helps to test the simulation model with the provided real-time values

of the system. Therefore, the furnace sections having multiple zones, as PHF (5 zones) and RTF (8 Zones) were designed in Simulink as shown in Figure 15.

The PLC program provided, controls the burner management system for the furnace where the temperatures of the set points are controlled based on operator input. The operator uses the annealing code standards made by ArcelorMittal to adjust the burner valves in order to attain the desired temperature of each zone in both furnace sections. The data of the previous process was recorded in .iba files, using IBA software that records all the data provided to and by the PLC. Therefore, the Simulink model has been designed in order to visualize how the system will respond based on the modified PLC program. Figure 15 shows the main screen of the SIMULINK model, when clicked on PreHeat Furnace block, it opens the circuit of signal flow which is shown in Figure 17. Also, when Radiant Furnace block is opened, it opens the circuit of signal flow which is shown in Figure 18. All these three figures just shows the flow of the signal but they're using only one logic in all these zones which is shown in Figure 19.

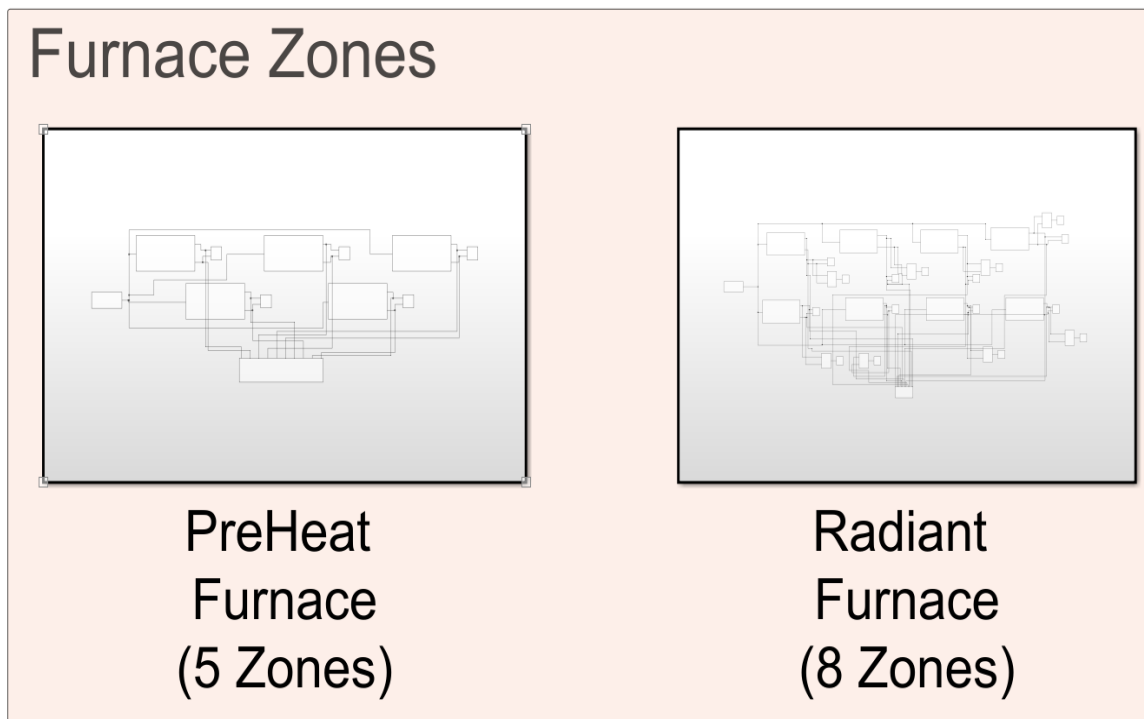


Figure 15: Furnace Zones (PreHeat Furnace with 5 zones and Radiant Furnace with 8 zones) developed in Simulink Model

6.2.1 Components Description

The Simulink model is designed using the Simulink library. The name and description of each component of the Simulink model is shown in Table 3.

Table 3: Description of the blocks and elements used in order to design the Simulink model for the ArcelorMittal's Furnace

Component	Description
Signal Builder	It creates and generates interchangeable groups of signals
Scope	It displays the input/output signal with respect to time domain.
Subtract block	It is used to subtract signals
Delay	It holds and delays its input by the specified sample period.
Thermal Reference	It is a thermal reference point, i.e. a point with an absolute zero temperature, with respect to which all the temperatures in the system are determined.
PID Block	It implements a PID Controller (PID, PI, PD, P or I only).
Controlled Temperature Source	It is an ideal source of thermal energy i.e. powerful enough to maintain specified temperature difference across the source regardless of the heat flow consumed by the system.
Temperature Sensor	It is an ideal temperature sensor, i.e. a device that determines the temperature differential measured between two points without drawing any heat.
Simulink-PS Converter	It converts the input Simulink signal into a physical signal.
PS-Simulink Converter	It converts a physical signal into a Simulink output signal.
Solver Configuration	It specifies the solver parameters that your model needs before you can begin simulation.

6.2.2 Description of Simulink Model

The model was designed in two major blocks as shown in Figure 15, but they are both passed with a signal which represents the temperature with respect to time, as shown in Figure 16. The Signal builder block is a useful tool, which allows us to generate a signal which imitates a real-life scenario of the desired temperature of the sheet changing with respect to time. The signal shown in the Figure 16 is created after analyzing the .iba data

provided by ArcelorMittal radiant tube furnace (RTF) temperature flow in between all the zones as per the time.

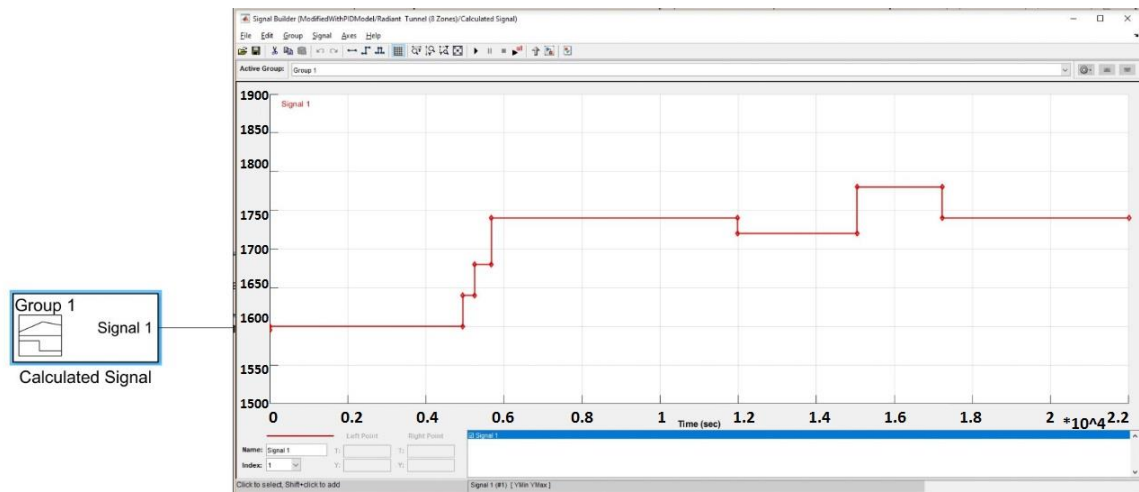


Figure 16: Signal Builder block with a prepared signal by matching with the data provided of the set points of the zones in .iba files, with Temperature (F) vs Time (sec)

The signal or the temperature at which the preheat furnace is kept, is a constant 1200 F as observed in the '.iba' data. Therefore, the signal wave created in the signal builder for PHD is kept at a constant temperature. However, it is possible to do the changes in the signal of the Preheat Furnace zone for future modifications or testing at a different temperature set points as shown in Figure 17. Since, the eight zones (red dotted circles) of the RTF are responsible for controlling the temperature of the sheet, the signal shown in Figure 16 is used for the Radiant Tube Furnace zone (yellow dotted circle) shown in Figure 18.

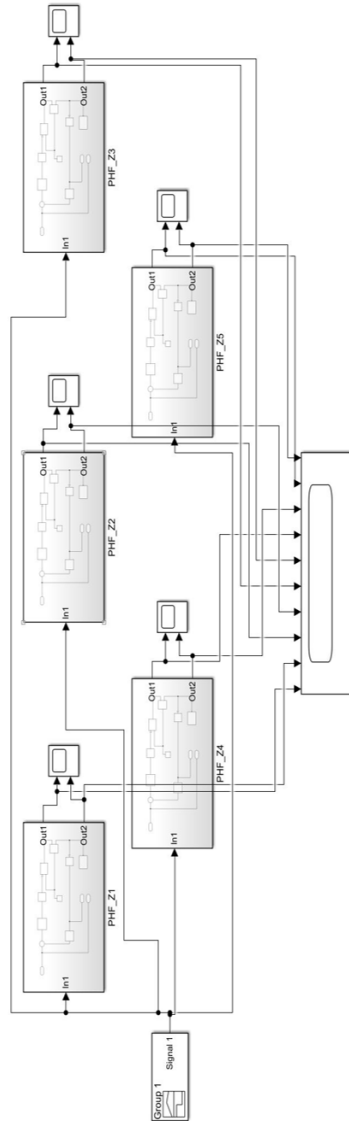


Figure 17: Preheat Furnace (5 Zones)

The signal, which is passed through each zone of RTF, has its own PID block and thermal analysis blocks which are already available in Simulink. It does the calculation for the set temperature to simulate a signal which tells how much time it will take to attain that set point temperature in the physical world. The signal builder (yellow dotted circle) sends the signal to each zone (red dotted circles) as shown in Figure 15. The process shown by each zone is the same inside, and they all release 2 signals in order to track the result of each zone (blue dotted triangles); one is the input signal, and the other is the calculated signal after PID.

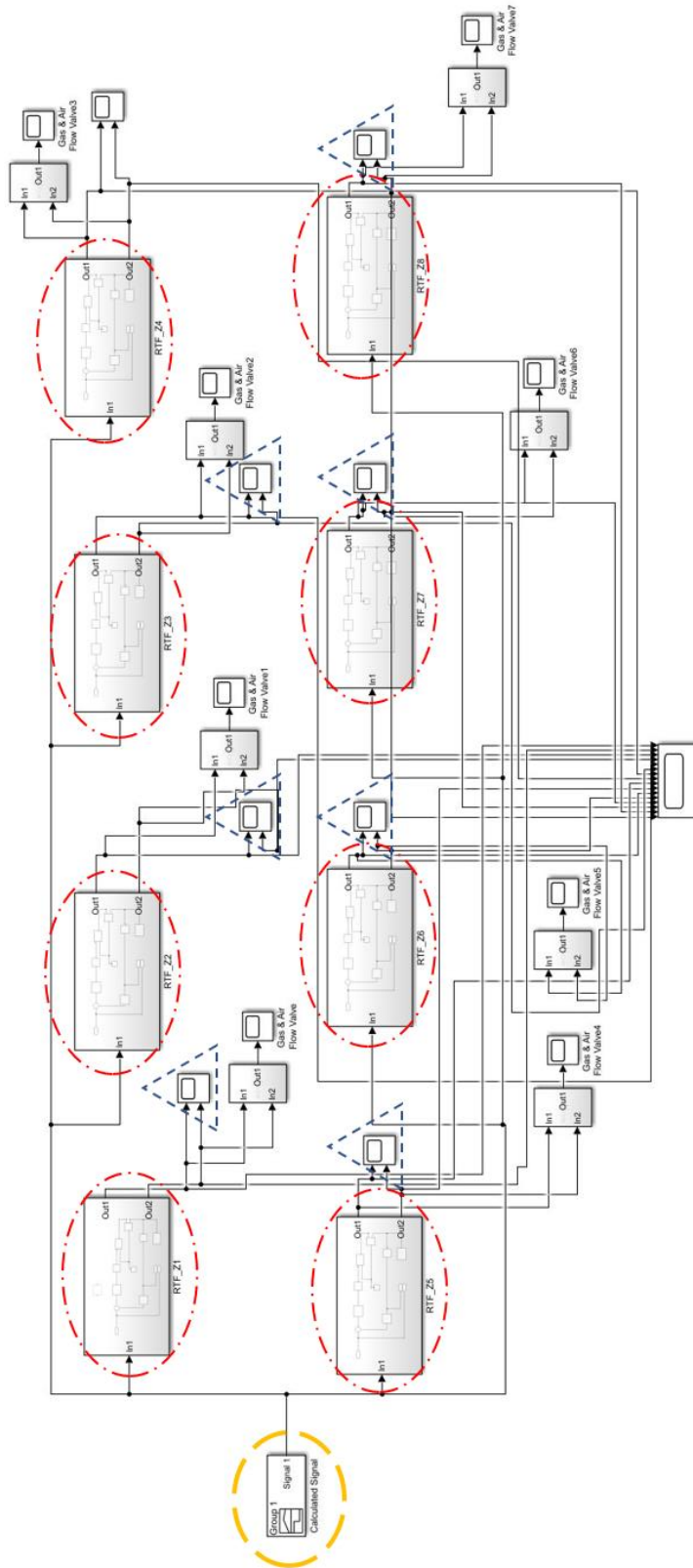


Figure 18: Radiant Tube Furnace (8 Zones)

The signal, which is passed to each zone, is shown by (1) in Figure 19, which is provided as an output via (2) and passed to the closed loop system of PID and thermal blocks. The signal first enters the PID block, which is set on Auto Tune and then goes to Simulink -PS Converter block, which converts the digital signal generated by the Simulink to the real physical world signal. The signal then goes through 'Controlled Temperature Source' which is also connected to a thermal reference in order to work as a real-life thermal source of heat. The signal is needed to be at the desired temperature after constantly monitoring the temperature via temperature sensor to show what ambient temperature has been attained by the furnace. Hence, to heat the sheet and then convert it back to Simulink signal via Simulink-PS Converter for the Simulink, the result is to show how it will react while opening and closing the gas and air flow valves.

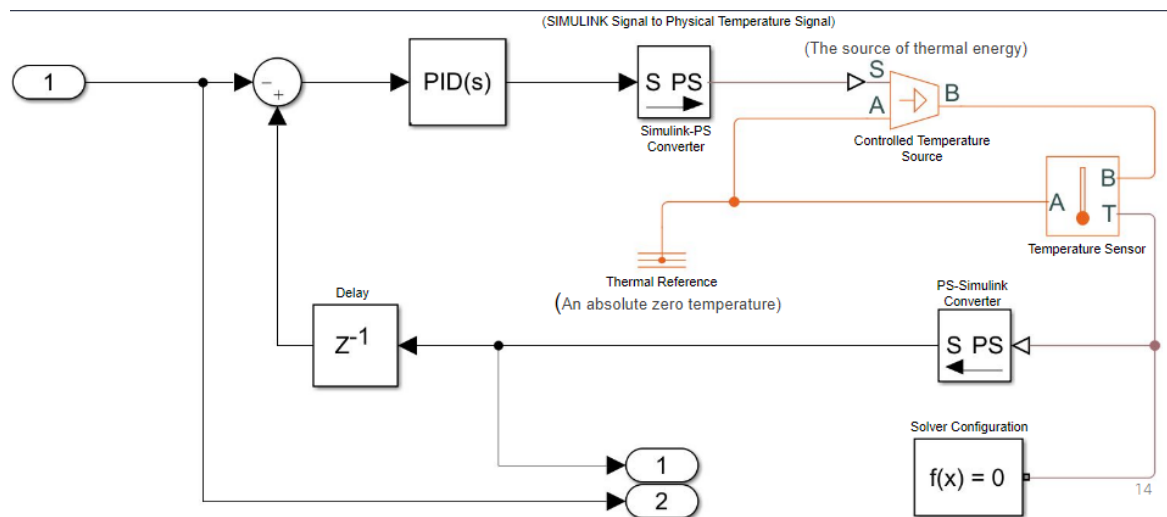


Figure 19: Closed Loop PID System for each zone in RTF which is being sent to Gas and Air Flow valve subsystem

The signal, which is initially created signal and PID calculated signal, are being sent to the scope as shown in Figure 20. The outputs of the subsystem shown in Figure 19 by 1 and 2 is going as an input to the subsystem of Air and Gas flow valve shown by 1 and 2 in Figure 20 (a). To determine the opening and closing of the gas and air valves when the temperature is reaching the desired temperature, a subsystem with computational block is made as shown in Figure 20 (b).

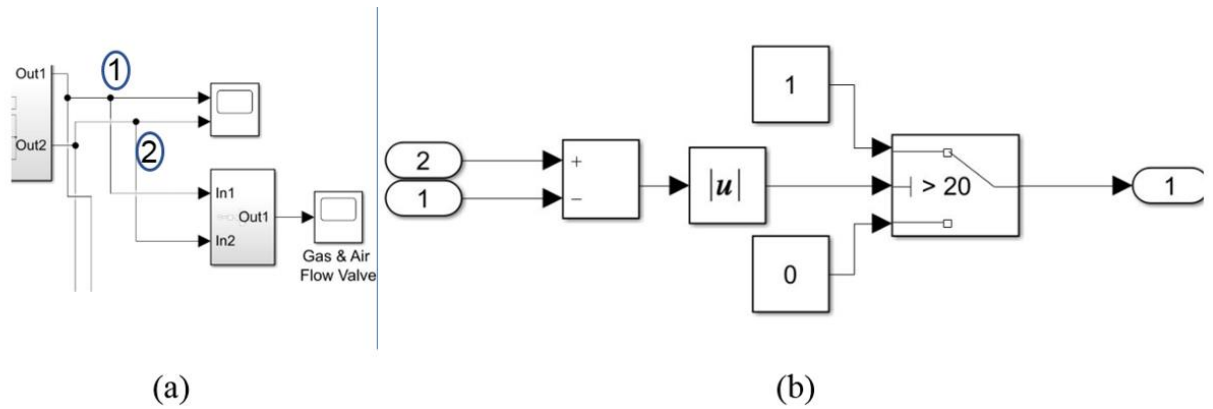


Figure 20: Designed gas and air flow subsystem to compute the opening and closing of gas and air flow valves

For example, if the temperature is required to be 1400F and the initial temperature is kept is at 0F, then by passing through the designed subsystem, the system will try to increase from 0 to 1400F. After getting closer to 1400F, the system might show overshoot depending on the PID. At the entire time when the gas and air flow valves are opened in order to raise the temperature; the subsystem will show output as 1. To show the gas and air flow valves are closed, the subsystem will show output as 0. The absolute value block is used to turn off the gas and air flow valves in 1380 to 1420F range.

6.3 Result

The Simulink Model of ArcelorMittal's Furnace zone ran successfully to imitate the actual thermal furnace data by passing the days' worth of data through the Simulink Model. The result also demonstrates the real time actuation of gas and air flow valve, as shown in Figure 21. The Simulink model result has been shared and approved by ArcelorMittal to move forward with the future work.

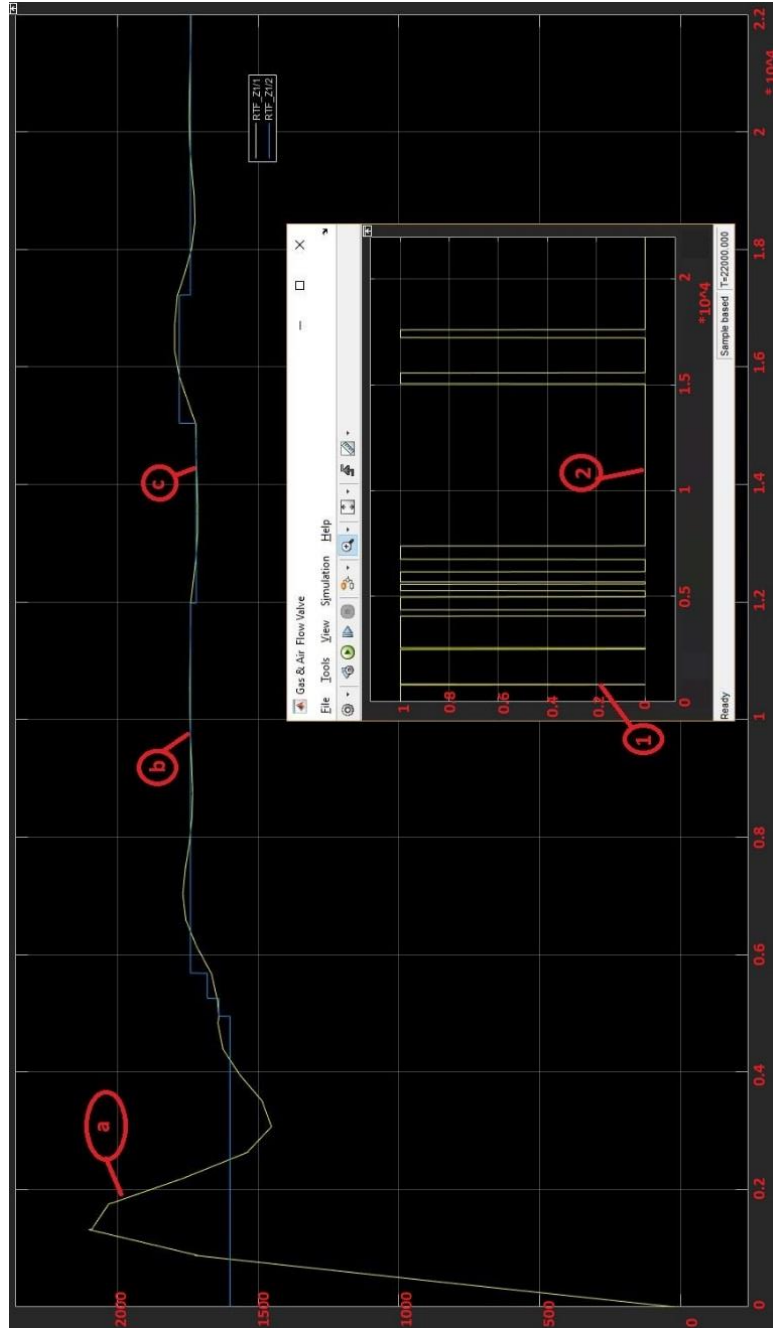


Figure 21: The scope result of ArcelorMittal Simulink Model representing the real-time operation of the furnace temperature and the opening and closing of the gas and air flow valves, with Temperature (F) vs Time (sec)

The result also shows the gas and air valve opening and closing time as 0 and 1, where 0 being the closing and 1 being the opening of gas and air flow valves. It means, when there's a need for the rise in temperature then the signal will show 1 and vice versa. The yellow line in the main result is representing the generated signal by the developed PID system and the blue line is representing the signal builder signal or the set points. At the beginning,

when the yellow line reaches the blue line, the gas and air flow valves are open, and when the temperature is in the range of the set point, it does the overshoot as marked by (a). The Gas and Air Flow valves are turned off as seen in the Gas and Air flow valve result, which shows the first drop or closing of the Gas and Air Flow Valve as marked by (1) in Figure 21.

When the system is at constant temperature or there's a steel sheet which is long and the zone is required to be at a particular temperature for a duration and the temperature of the zone is already at that level as marked by (b), the Gas and Air flow valves remain turned off for that duration as marked by (2). Moreover, the Gas and Air Flow Valves remains off for optimizing the system, if the next sheet that enters the furnace is supposed to be at a close temperature and there's not that significant of a difference. In our case it is assumed that the next drop of the set point temperature marked by (c), is in ± 20 F variability.

6.4 Future Work

A senior design team at Michigan Tech has worked on adding the thermodynamics equation to the Simulink model as shown in Figure 22. The updated model is using the same developed signal after computing the heat transfer data values. The Matlab function blocks has been used to do the calculation in the Matlab and being called in the Simulink model. The general equations for converting inch to meter, Fahrenheit to Kelvin, Belt Speed to Time, Main Temperature and Kelvin to Fahrenheit is done using Matlab functions. At the end it goes to the initial system, shown with "Initial System block" in grey color which does the entire signal flow which was explained in Figure 18.

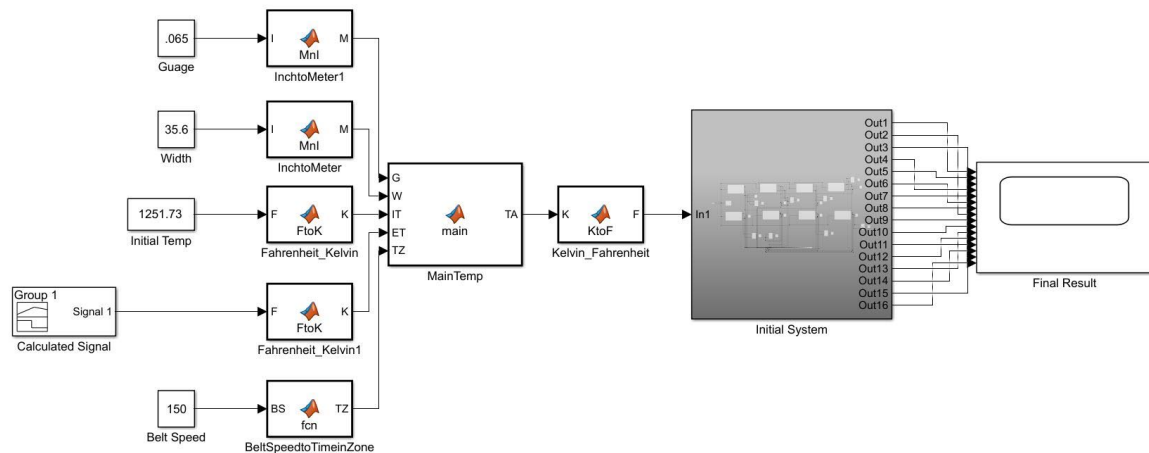


Figure 22: The Simulink Model after adding the temperature calculations block into the initial system model

The initial system block is the same model shown in Figure 18 but inside a subsystem. The updated model will be able to compute the time to heat and time to cool for the metal sheet. The program for the Matlab functions developed are attached in Appendix B. The designed Simulink model will also send the optimized set points to the PLC directly which will make the job of the operator easy. The operator won't need to enter all the set points but will only need to insert the annealing code of the sheet. The annealing code standards defined by ArcelorMittal demand the different set points for different code, which this upgrade should be able to do automatically.

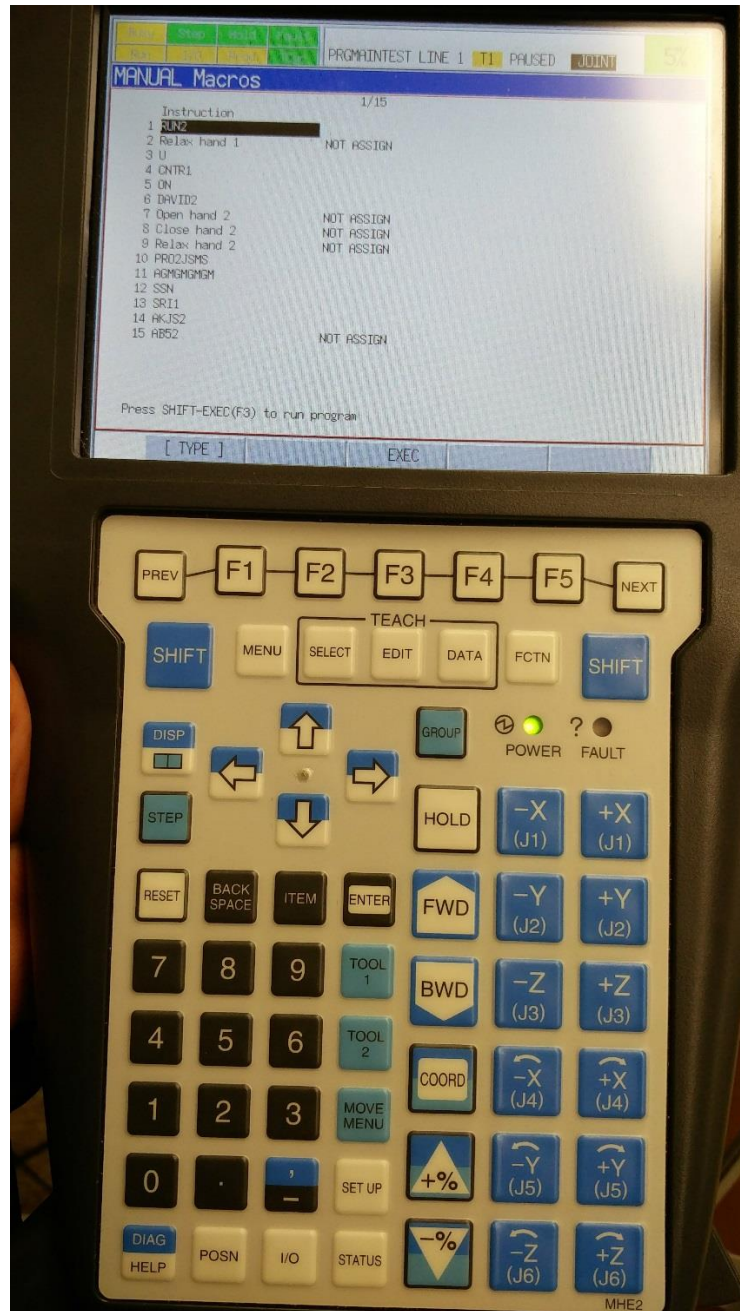
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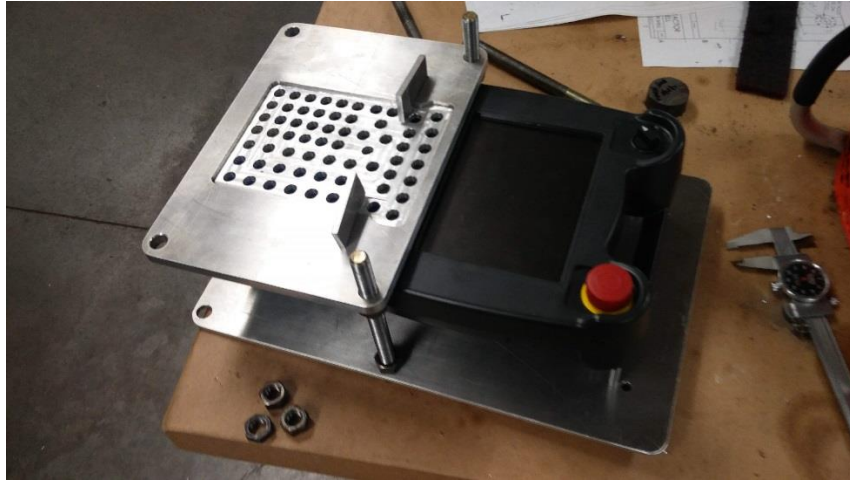
11. Hasegawa, A. (1994). Development of a strip temperature control system with adaptive generalized predictive control. 1994 Proceedings of IEEE International Conference on Control and Applications. doi: 10.1109/CCA.1994.381489

Appendix A

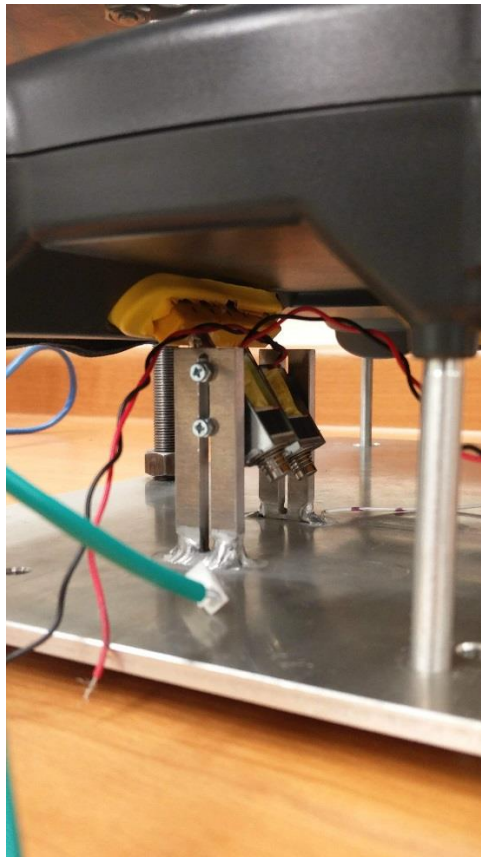
- FANUC LrMate 200iC Teach Pendant keys



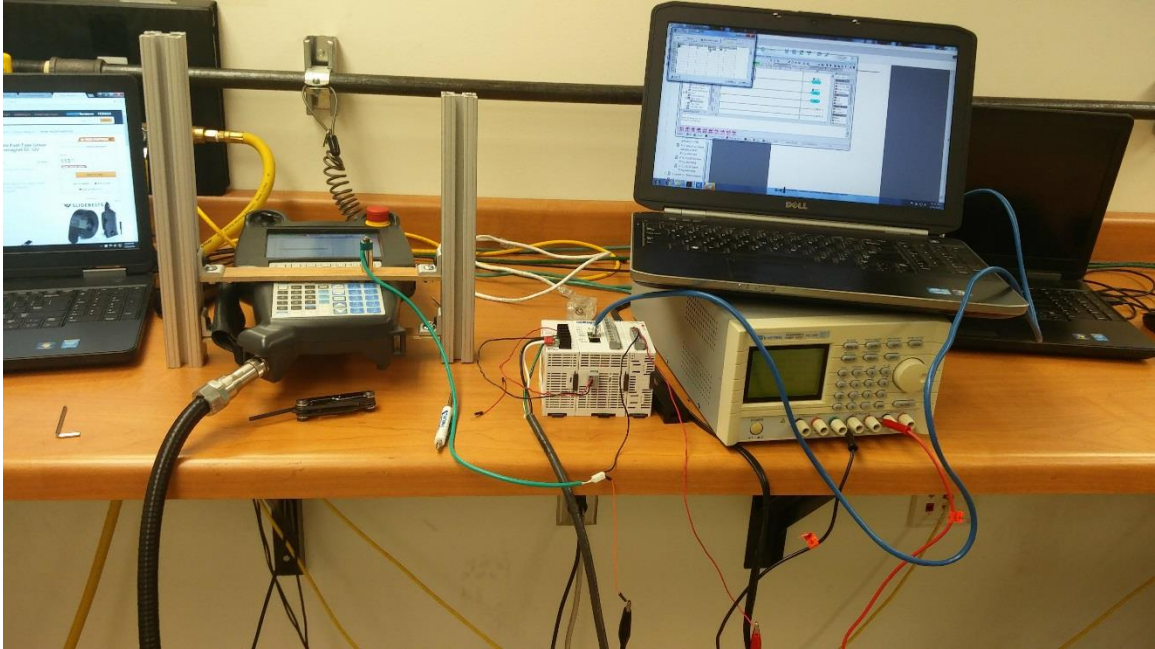
- **Placing the teach pendant in between bottom and middle plate**



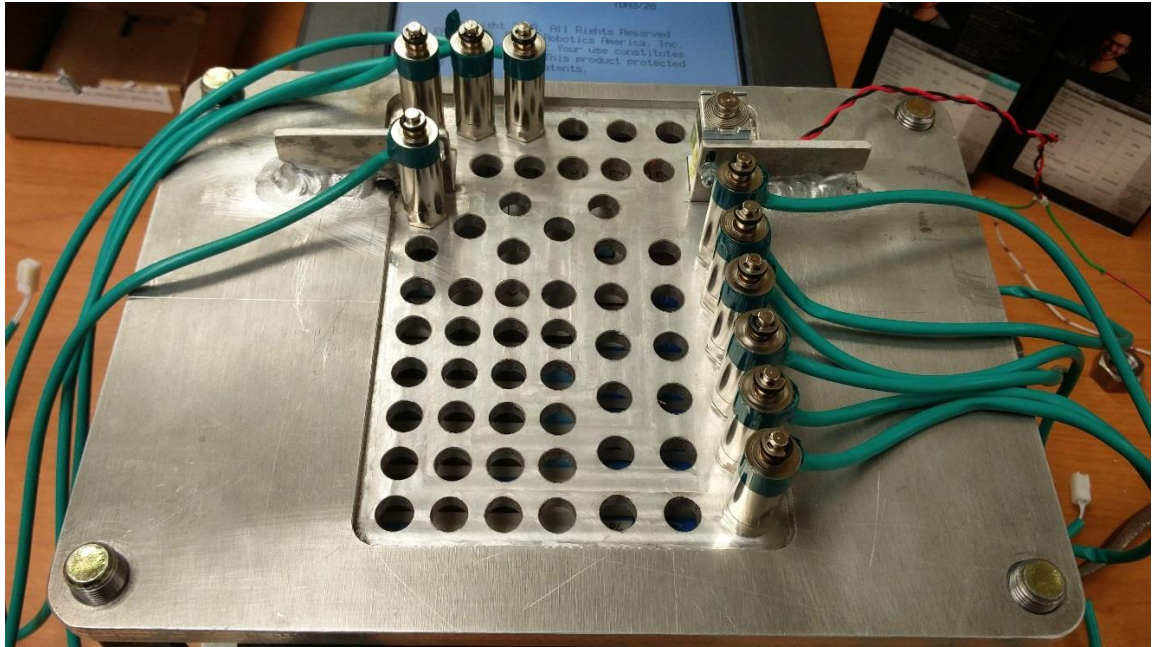
- **Latching type actuators for deadman switch**

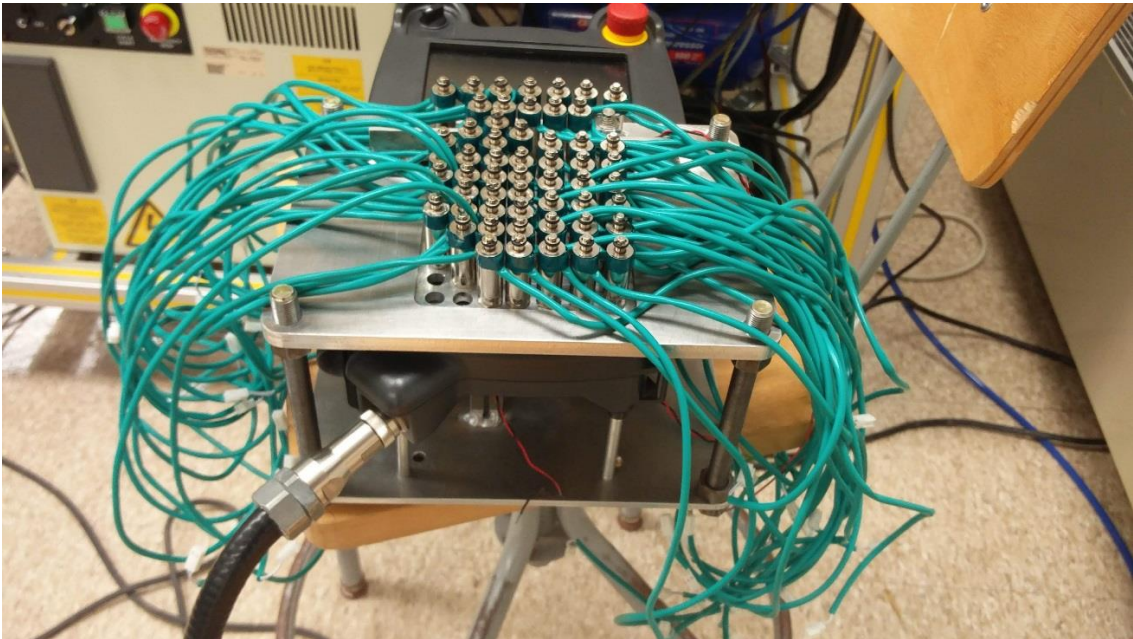
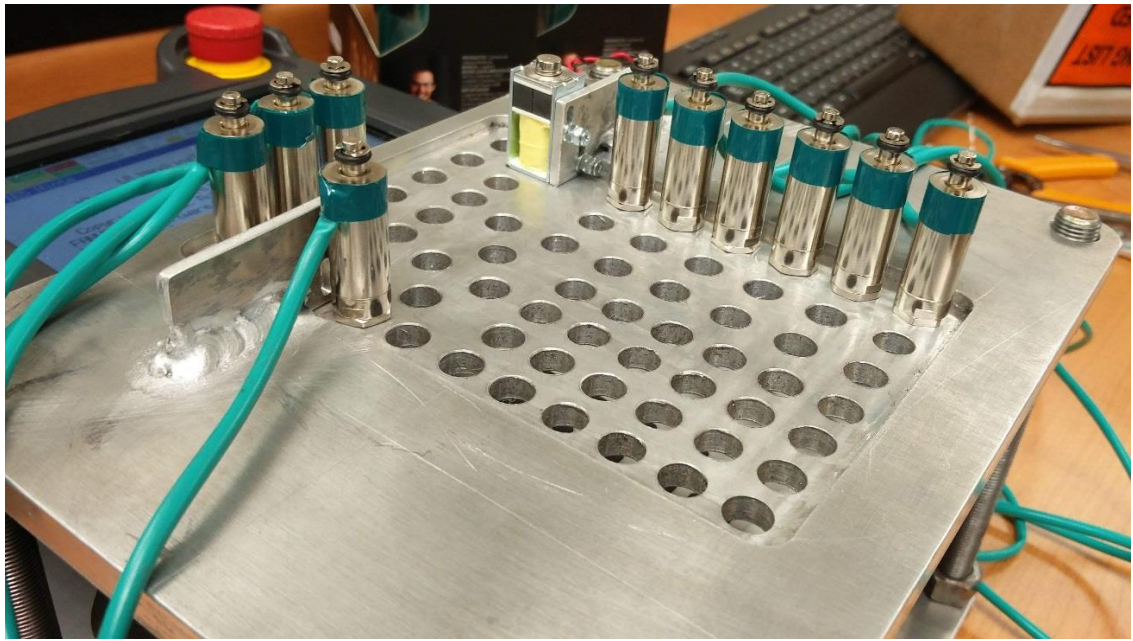


- Initial testing of the push type actuator for one key



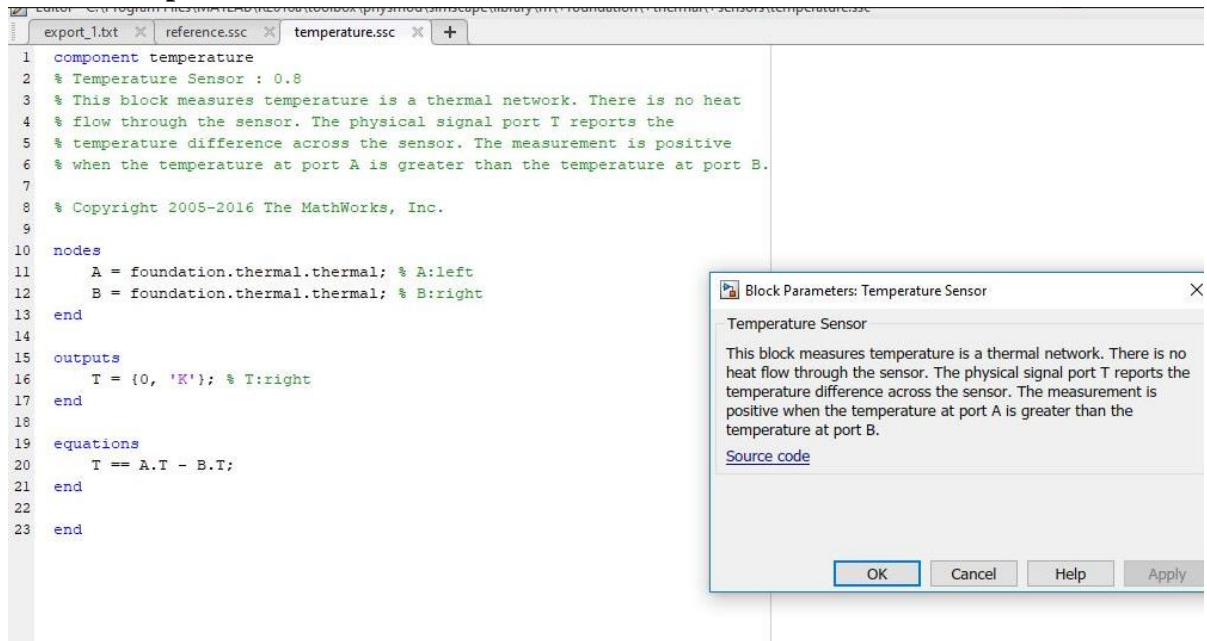
- Placing all the actuators on the middle plate





Appendix B

- Source codes for Temperature Sensor, Thermal Reference, Controlled Temperature Source



The screenshot shows the MATLAB editor with three tabs: 'export_1.txt', 'reference.ssc', and 'temperature.ssc'. The 'temperature.ssc' tab is active, displaying the following code:

```
1 component temperature
2 % Temperature Sensor : 0.8
3 % This block measures temperature is a thermal network. There is no heat
4 % flow through the sensor. The physical signal port T reports the
5 % temperature difference across the sensor. The measurement is positive
6 % when the temperature at port A is greater than the temperature at port B.
7
8 % Copyright 2005-2016 The MathWorks, Inc.
9
10 nodes
11     A = foundation.thermal.thermal; % A:left
12     B = foundation.thermal.thermal; % B:right
13 end
14
15 outputs
16     T = {0, 'K'}; % T:right
17 end
18
19 equations
20     T == A.T - B.T;
21 end
22
23 end
```

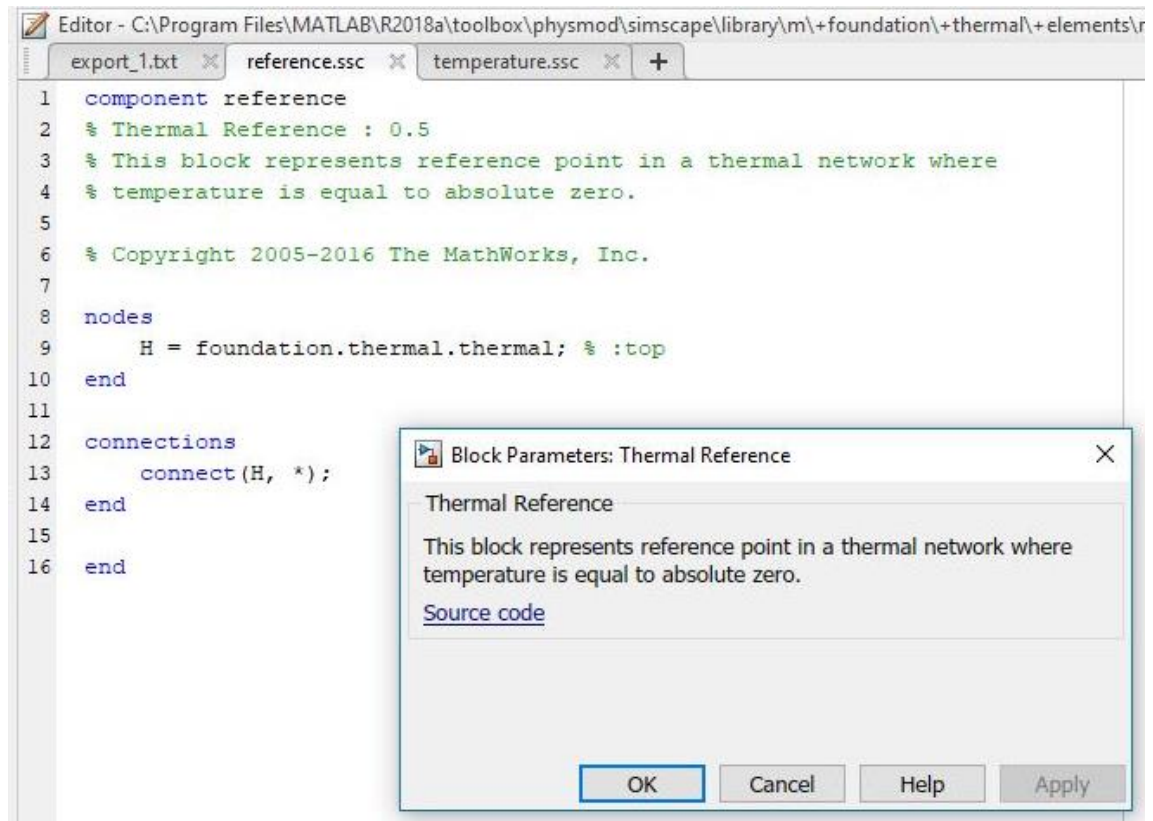
Overlaid on the right is the 'Block Parameters: Temperature Sensor' dialog box. It contains the following text:

Temperature Sensor

This block measures temperature is a thermal network. There is no heat flow through the sensor. The physical signal port T reports the temperature difference across the sensor. The measurement is positive when the temperature at port A is greater than the temperature at port B.

[Source code](#)

Buttons: OK, Cancel, Help, Apply



The screenshot shows the MATLAB editor with three tabs: 'export_1.txt', 'reference.ssc', and 'temperature.ssc'. The 'reference.ssc' tab is active, displaying the following code:

```
1 component reference
2 % Thermal Reference : 0.5
3 % This block represents reference point in a thermal network where
4 % temperature is equal to absolute zero.
5
6 % Copyright 2005-2016 The MathWorks, Inc.
7
8 nodes
9     H = foundation.thermal.thermal; % :top
10 end
11
12 connections
13     connect(H, *);
14 end
15
16 end
```

Overlaid on the right is the 'Block Parameters: Thermal Reference' dialog box. It contains the following text:

Thermal Reference

This block represents reference point in a thermal network where temperature is equal to absolute zero.

[Source code](#)

Buttons: OK, Cancel, Help, Apply

Editor - C:\Program Files\MATLAB\R2018a\toolbox\physmod\simcape\library\m\+foundation\+thermal\+sources\controlled_temperature.ssc

export_1.txt x reference.ssc x temperature.ssc x controlled_temperature.ssc x +

```

1 component controlled_temperature
2 % Controlled Temperature Source
3 % This block represents an ideal energy source in a thermal network that
4 % can maintain a controlled temperature difference regardless of the heat
5 % flow rate. The temperature difference is set by the physical signal port
6 % S. A positive temperature difference causes the temperature at port B to
7 % be greater than the temperature at port A.
8
9 % Copyright 2005-2016 The MathWorks, Inc.
10
11 inputs
12     S = {293.15, 'K'}; % S:bottom
13 end
14
15 nodes
16     A = foundation.thermal.thermal; % A:bottom
17     B = foundation.thermal.thermal; % B:top
18 end
19
20 variables (Access=private, Conversion=relative)
21     T = {0, 'K'}; % Temperature difference
22 end
23
24 variables (Access=private)
25     Q = {0, 'W'}; % Heat flow rate
26 end
27
28 branches
29     Q : B.Q -> A.Q;
30 end
31
32 equations
33     T == B.T - A.T;
34     T == S;
35 end
36
37 end

```

Block Parameters: Controlled Temperature Source

Controlled Temperature Source

This block represents an ideal energy source in a thermal network that can maintain a controlled temperature difference regardless of the heat flow rate. The temperature difference is set by the physical signal port S. A positive temperature difference causes the temperature at port B to be greater than the temperature at port A.

[Source code](#)

OK Cancel Help Apply

- **Modified PLC program for future work**

```

Editor - Block: ModifiedWithPIDModel_HT/Radiant Tunnel (8 Zones)/Kelvin_Fahrenheit
Radiant Tunnel(8 Zones)/BeltSpeedtoTimeinZone x Radiant Tunnel(8 Zones)/MainTemp
1 function F = KtoF(K)
2   %#codegen
3
4   F = ((K - 273.15) * (9/5)) + 32;

```

```

Editor - Block: ModifiedWithPIDModel_HT/Radiant Tunnel (8 Zones)/Fahrenheit_Kelvin
+1 Radiant Tunnel(8 Zones)/Fahrenheit_Kelvin x Radiant Tunnel(8 Zones)/BeltSpeed
1 function K = FtoK(F)
2   %#codegen
3
4   K = ((F-32) * (5/9)) + 237.15;

```

```

Editor - Block: ModifiedWithPIDModel_HT/Radiant Tunnel (8 Zones)/InchtoMeter
+2 Radiant Tunnel(8 Zones)/InchtoMeter x Radiant Tunnel(8 Zones)/BeltSpeedtoTimeinZone
1 function M = MnI(I)
2   %#codegen
3
4   M = I/39.37;

```

```

Editor - Block: ModifiedWithPIDModel_HT/Radiant Tunnel (8 Zones)/MainTemp
Radiant Tunnel(8 Zones)/MainTemp x +
1 function TA = main(G,W,IT,ET,TZ)
2   %#codegen
3
4   TA = (((G*W*7850*41000*IT) / (TZ)) * G) / (50*W)) + ET;

```

```

Editor - Block: ModifiedWithPIDModel_HT/Radiant Tunnel (8 Zones)/BeltSpeedtoTimeinZone
Radiant Tunnel(8 Zones)/BeltSpeedtoTimeinZone x Radiant Tunnel(8 Zones)/MainTemp x
1 function TZ = fcn(BS)
2   %#codegen
3
4   TZ = ((59.716) / ((BS/3.281) / (60)));

```