Industrial Project: Mini-PLC

Team 1

Prince Sakariya (4021094)

Kuldeep Mangaroliya (4020130)

Dhruvin Vekariya (4021194)

Tejas Shastry (4021043)

Shardul Joshi (4021135)

Vaibhav Gujarati (4021195)

Customer: Prof. Dr. -Ing. Florian Mühlfeld

Supervisor: M. Eng. Fabian Dax

Date of submission: 16th May 2024

Abstract

This project involves the creation of a Programmable Logic Controller (PLC) utilizing an Arduino microcontroller (Uno/Mega) as its core component. To ensure compatibility with standard PLC operating voltages, we developed the necessary power electronics surrounding the Arduino. Our PLC configuration includes 8 input and 8 output channels, providing ample capacity for various automation tasks. The entire system was meticulously implemented on a custom-designed Printed Circuit Board (PCB), which was created using Altium Designer. Additionally, we designed, and 3D printed a bespoke housing to encase the PLC, ensuring both functionality and durability. This integrated approach highlights the feasibility of using Arduino in industrial automation applications, combining hardware design and digital fabrication techniques.

Acknowledgement

We would like to extend our heartfelt gratitude to everyone who contributed to the successful completion of this project. First and foremost, we thank our Client Prof. Dr. Florian Mühlfeld for giving us the opportunity to work on this incredible project. It could not have been possible without our supervisor, Mr. Fabian Dax, we are grateful for their invaluable guidance, support, and encouragement throughout the project. Your expertise and insights were instrumental in overcoming the technical challenges we faced.

We also wish to acknowledge the support provided by our institution, Technische Hochschule Würzburg-Schweinfurt, for granting us access to the necessary resources and facilities. Special thanks to the technical staff at the Robotics lab for their assistance and to our peers for their constructive feedback and camaraderie.

Contents

Abstract ii
Acknowledgement iii
List of figures v
List of abbreviations v
1 Introduction 1
2 Key Components of the Development 2
2.1 Digital Input Module 2
2.2 Digital Output Module 4
2.3 Powering Arduino 6
2.4 PCB design 7
2.5 Housing for the Electronics 12
4 Loading and running Mini-PLC 14
5 Conclusion 15
6 Appendix 16
Table for Work Contributions 17
Statutory Declaration 18

List of figures

Figure 1: Circuit Diagram of the Input Module of the Mini-PLC. 2
Figure 2: Optocoupler PC817 Datasheet 3
Figure 3: Circuit Diagram of the Output Module of the Mini-PLC. 4
Figure 4: Simulation of Output Module with inductive load without(top) and with(bottom) flyback diode 5
Figure 5: Top View of HW-140 Buck Boost Converter, ... 6
Figure 6: Multi-Channel Design Hierarchical approach Altium Designer. 7
Figure 7: Schematic for I/O Itegration from Arduino to Input and Output Module. 8
Figure 8: PCB layout of Mini-PLC 10
Figure 9: PCB after assembly with DC-DC Buck Boost converter. 11
Figure 10: Design for the Top Plate (Dimensions in mm) 12
Figure 11: 3D Image of Top Plate 12
Figure 12: Design for the Housing Base (Dimensions in mm) 13
Figure 13: 3D Image of the Housing Base 13
Figure 14: Top plate pointed outlook 14
Figure 15: The Final Product 15

List of abbreviations

PLC	Programmable Logic Controller
I/O	Input/Output
USB	Universal Serial Bus
LED	Light-emitting diode
DIM	Digital Input Module
MOSFET	Metal-oxide-semiconductor field-effect transistor
IGBT	Insulated Gate Bipolar Transistors
P-Channel	Positive Channel
PCB	Printed Circuit Board
IDE	Integrated development environment
MCAD	Mechanical Computer-Aided Design
3D	3 Dimensional

1 Introduction

A PLC is a central controlling unit in most of the industrial processes and motion. A PLC reads inputs like sensors and switches, makes decisions based on programmed instructions and gives output commands to control devices such as motors or valves. This technical report briefly investigates all requirements and presents the development steps for Arduino based Mini-PLC Project.

Table 1: Motivation for the Mini-PLC project.

Customization	Arduino allows to tailor the PLC to specific needs and application, without the need of expensive licenses.
Cost-effectiveness	Arduino boards and components needed for this project are relatively affordable than commercial PLCs.
Accessibility	As an open-source platform, Arduino has vast online community and resources to aid in development i.e. OpenPLC.
Scalability	Arduino-based solutions allows us to scale from simple to complex systems.
Learning opportunity	Development of Mini-PLC provides valuable learning to gain deeper understanding of automation systems.

The aim of this project is to build a PLC hardware, which operates using an Arduino board and fulfils the following requirements:

- Usable for Arduino UNO and Arduino Mega.
- Arduino Board must be easily removable.
- 16 digital I/O port with Banana Plug.
- I/O interface with Voltage level up to 30V.
- LEDs for I/O level indication.
- On-Off-Moment Switch for input control.
- External Power Supply 5-30V, which defines I/O voltage level.
- Powering Arduino from external power supply or USB port.
- 165mm breadboard on top (accessible via 117mm wires).
- It should fit in a 300x200 mm Euro-box (incl. Power Supply).

2 Key Components of the Development

The project dictates three primary tasks in electrical domain to regulate conversion and switching modules from 5-30V for external I/O to 5V signal for processing on Arduino board.

2.1 Digital Input Module

The implementation of the Digital Input Module (DIM) is done using optocouplers. This section goes in depth on the construction of the DIM.

There are two possibilities for giving an input to Mini-PLC.

1) By connecting a Digital Sensor (Proximity sensor/ Switch).
2) By using the inbuilt On-Off-Momentary Switch.

As per the requirements, the DIM should accept input signals ranging from 5-30V, whereas the operating voltage of an Arduino is only 5V. Therefore, an intermediate module is necessary, capable of converting this a signal higher than 5V such that it can be accurately and safely sensed by the Arduino.

An optocoupler is a widely used component for galvanic isolation[1] across it's input and output side. **Caution: Do NOT connect the two grounds** (5-30V GND and Arduino GND) for a proper galvanic isolation. It has optical coupling mechanism for high-speed-signal transmission and protection against voltage spikes. which makes it ideal component for input module of this project.

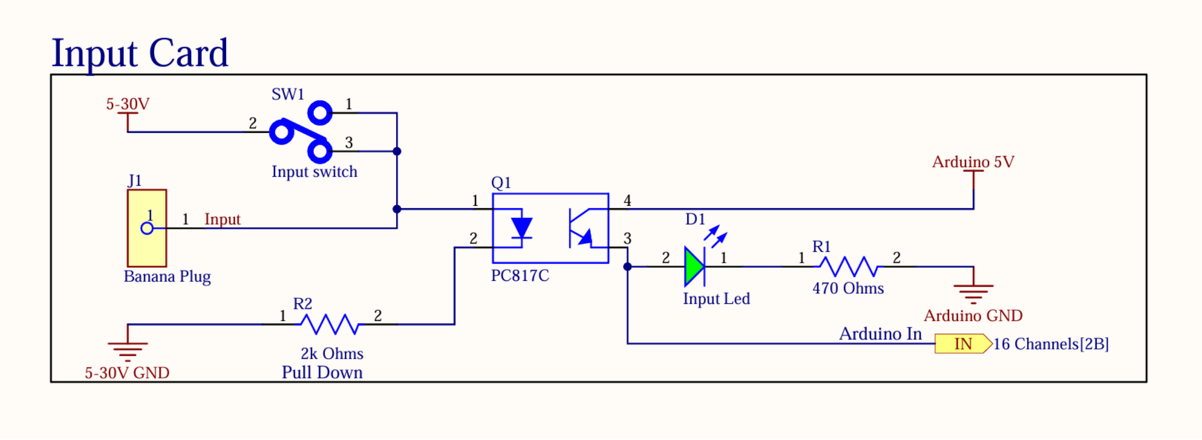

Figure 1: Circuit Diagram of the Input Module of the Mini-PLC.

We use PC817[2] because of its compact size and higher voltage capabilities. In Figure 1, the LED side (pins 1 and 2) of PC817 is connected to external input signal and the phototransistor side (pins 3 and 4) is connected to Arduino and input indicator led.

An external input signal of 5-30V can be directly connected to the female banana plug or via the built-in switch. It is **important to note** that the input module is of the *sinking type*[3], as it can be seen in Figure 1, indicated by the pull-down resistor R2.

---

[1] *Galvanic Isolation*: https://en.wikipedia.org/wiki/Galvanic_isolation
[2] *PC817 Optocoupler*: https://global.sharp/products/device/lineup/data/pdf/datasheet/PC817XxNSZ1B_e.pdf
[3] *Sinking type*: https://www.realpars.com/blog/sinking-and-sourcing

When an input signal is applied, IR led inside the PC817 (pins 1 and 2) illuminates, and the signal is pulled down by R2. This action closes the phototransistor gate of PC817 (pins 3 and 4), enabling the Arduino to detect a 5V signal (refer to Port In connected to anode of D1). Led D1 lights up to indicate the detection of a digital input signal.

Calculations:

■ **Electro-optical Characteristics** (T_a=25℃)

Parameter			Symbol	Condition	MIN.	TYP.	MAX.	Unit
Input	Forward voltage		V_F	I_F=20mA	–	1.2	1.4	V
	Peak forward voltage		V_{FM}	I_{FM}=0.5A	–	–	3.0	V
	Reverse current		I_R	V_R=4V	–	–	10	μA
	Terminal capacitance		C_t	V=0, f=1kHz	–	30	250	pF
Output	Dark current		I_{CEO}	V_{CE}=50V, I_F=0	–	–	100	nA
	Collector-emitter breakdown voltage		BV_{CEO}	I_C=0.1mA, I_F=0	80	–	–	V
	Emitter-collector breakdown voltage		BV_{ECO}	I_E=10μA, I_F=0	6	–	–	V
Transfer charac–teristics	Collector current		I_C	I_F=5mA, V_{CE}=5V	2.5	–	30	mA
	Collector-emitter saturation voltage		$V_{CE(sat)}$	I_F=20mA, I_C=1mA	–	0.1	0.2	V
	Isolation resistance		R_{ISO}	DC500V, 40 to 60%RH	5×10^{10}	1×10^{11}	–	Ω
	Floating capacitance		C_f	V=0, f=1MHz	–	0.6	1.0	pF
	Cut-off frequency		f_C	V_{CE}=5V, I_C=2mA, R_L=100Ω, −3dB	–	80	–	kHz
	Response time	Rise time	t_r	V_{CE}=2V, I_C=2mA, R_L=100Ω	–	4	18	μs
		Fall time	t_f		–	3	18	μs

Figure 2: Optocoupler PC817 Datasheet

R2 is in series with internal IR LED of the PC817, for which V_F = 1.2V and I_F = 20mA (see Figure 2).

$$R_2 = \frac{30V - V_F}{I_F}$$

$$R_2 = 1.44\ k\Omega \approx \boldsymbol{2k\Omega}$$

It's important to calculate the power dissipation of R2 for prolonged life. Power is calculated as following. During testing I_F was measured at 50mA for input voltage 30V and V_F = 1.2V.

$$P_{R_2} = I_F^2\, R_2 = \boldsymbol{0.5\ W}$$

Similarly, R1 was calculated as approximately **470Ω.**

2.2 Digital Output Module

The output signal must be able to supply voltages between 5-30V (as dictated by the external power supplied), enough current to power relays, solenoids, etc. and handle inductive loads. Arduino cannot provide fulfil these requirements. Thus, an output module is necessary.

MOSFET (Metal oxide semiconductor field effect transistor), IGBT (Insulated Gate Bipolar Transistors) or Mechanical relay can be used for this purpose. MOSFET was chosen because it is much more affordable than an IGBT while providing far better switching speeds and longer lifespan when compared to a mechanical relay.

For this a P-channel logic-level MOSFET is used in this project. A logic level MOSFET was chosen so that no additional components would be required to drive the MOSFET. The reason for using a P-channel MOSFET is to provide sourcing type output.

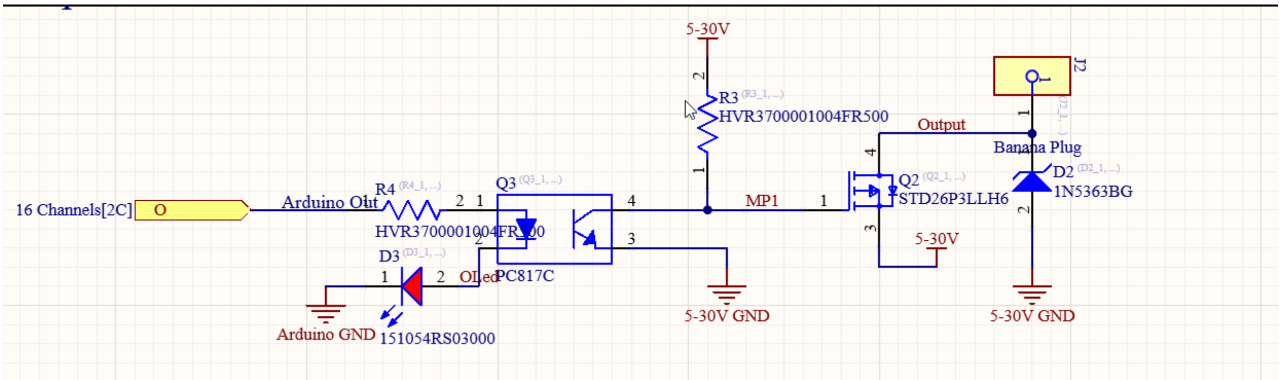

Figure 3: Circuit Diagram of the Output Module of the Mini-PLC.

In the above image, the Arduino Out net receives the 5V output from the Arduino. When a high signal is received, it excites the optocoupler (Q3) and powers the LED (D3) on. When the optocoupler is in its excited state, it allows current to pass between pins 3 and 4. Pin 4 is connected to the pull up resistor (R3) and the gate of MOSFET (Q2). When the optocoupler is in its unexcited state, the gate is pulled up to 5-30V. This keeps the MOSFET in off state. However, when the connection between optocoupler pins 3 and 4 is established (i.e. Arduino output is high), the gate is pulled down to 0V. This turns on the MOSFET, thus powering the PLC output.

Flyback Diode:

Additionally, a flyback diode (D2) was added to protect the PLC from spikes caused by an inductive load, which can be seen from below Figure 4.

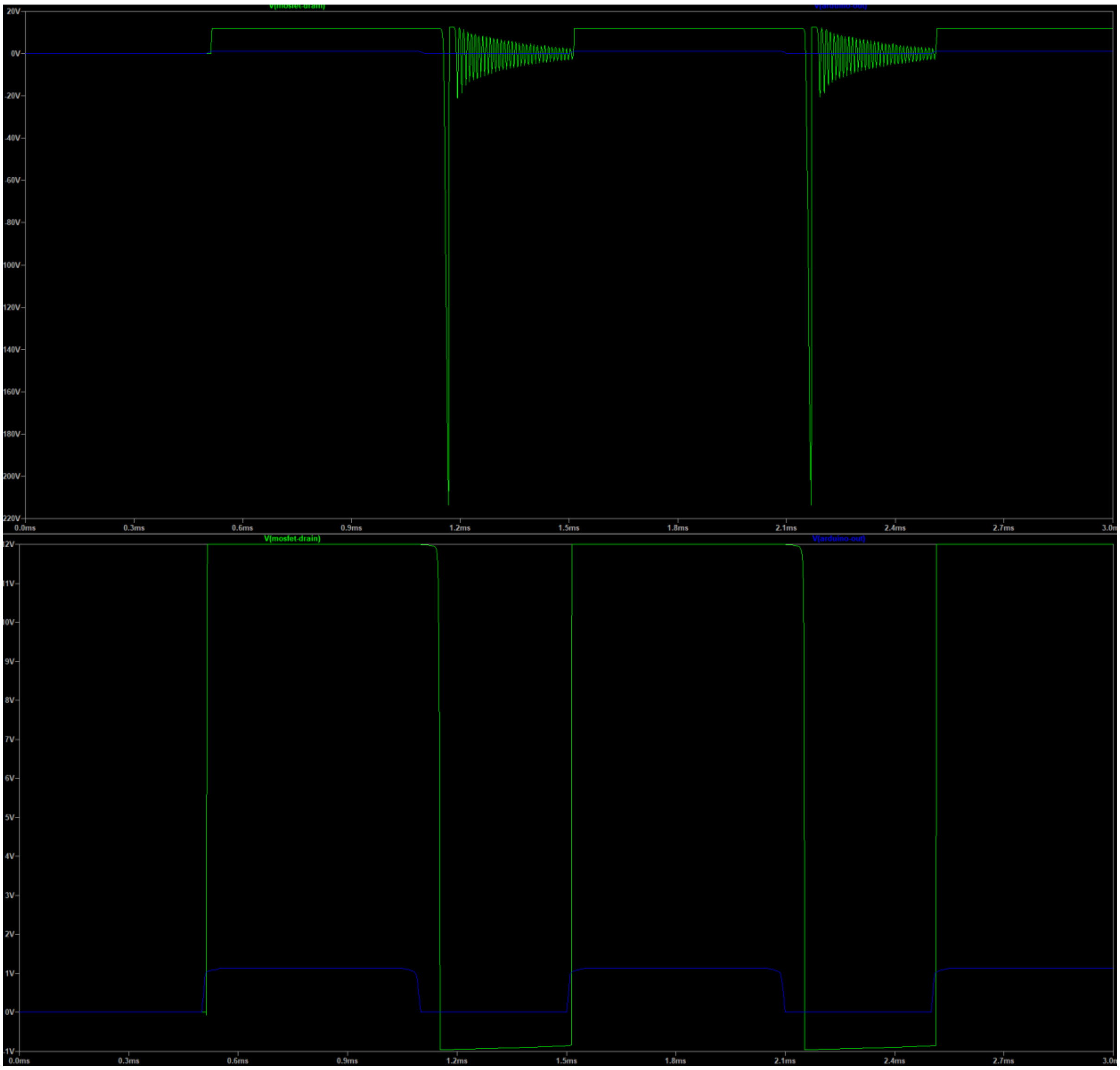

Figure 4: Simulation of Output Module with inductive load without(top) and with(bottom) flyback diode

This image showcases simulation of output module with inductive load in LTspice software. Where green line represents measured output voltage at banana plug and blue represent voltage at Arduino Out. As we can see, when we stop applying voltage at inductive load, due to back current it generates large voltage spikes which can cause damage to circuit. Solution to this problem was to add diode between PLC outputs (banana port J2) and ground in reverse bias, which can ground high voltage spikes. A Zener diode was chosen over Schottky diode for this purpose due to its more aggressive damping characteristics.

2.3 Powering Arduino

In this project, the Arduino is powered using the *Vin pin* on board, which operates in the range 7V to 12V. This input voltage span can make things easy because of changing external voltage supply. Special care must be taken to **not connect** the *Vin pin* and the GND pin incorrectly, this permanently damages the Arduino.

A DC-DC buck boost step up/down converter, which can covert 5-30V external power supply to constant acceptable *Vin pin* voltage i.e. HW-140 DC-DC buck converter is used. It is set for conversion from 5-30V to 9V for *Vin pin* of Arduino board. It has on mount display which shows input or output voltage and current in real time. It also acts as isolation between Arduino board and external voltage supply, given more then 30V, it stops operating. After turning the screws for desired output voltage and current, it is ready to use.

Figure 5: Top View of HW-140 Buck Boost Converter,

The wiring of the DC-DC buck boost step up/down converter can be found in the Schematics in the Appendix.

2.4 PCB design

Physical wiring of all components for 8 inputs and 8 outputs with socket headers to connect to the Arduino board is complex due to the large number of connections. Using a PCB reduces size and improves repeatability and reliability of the electronics.

The PCB was designed mainly in 3 Steps.

1) Schematic design
2) PCB Layout
3) Generation of Fabrication Outputs[4]

The PCB design was created using Altium Designer software. Using this software comes with many advantages such as collaborative design by multiple users and version control features. We used the Multi-Channel Design[5] feature provided by Altium Designer and divided the schematic in four sections:

1) 8 channel Input and Output (Parent directory).
2) Input and Output Module.
3) Power Supply.
4) Arduino Uno and Mega IO integration.

Sections 2, 3 and 4 are integrated into Section 1, where Section 2 is repeated 8 times (see Figure 6) using the REPEAT keyword. This powerful feature allows for faster and more comprehensive schematic design.

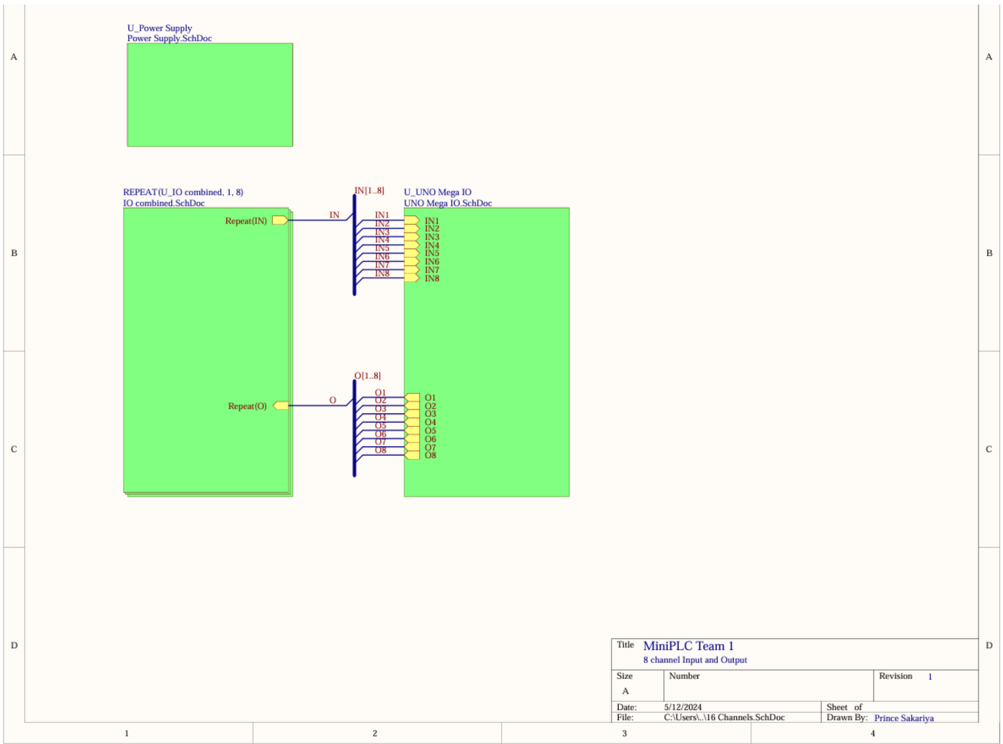

Figure 6: Multi-Channel Design Hierarchical approach Altium Designer.

[4] *Fabrication Outputs*: https://techdocs.altium.com/node/296948
[5] *Multi-Channel Design and the repeat keyword*: https://www.altium.com/documentation/altium-designer/multi-sheet-hierarchical-designs?version=17.1#creating-a-multi-channel-design

One of the most important tasks is to map the pins to their physical addresses[6] according to OpenPLC for Arduino Uno and Mega (see Table 2 and Table 3). Figure 7 shows the schematic of the implementation with the DIM and Digital Output Module (DOM).

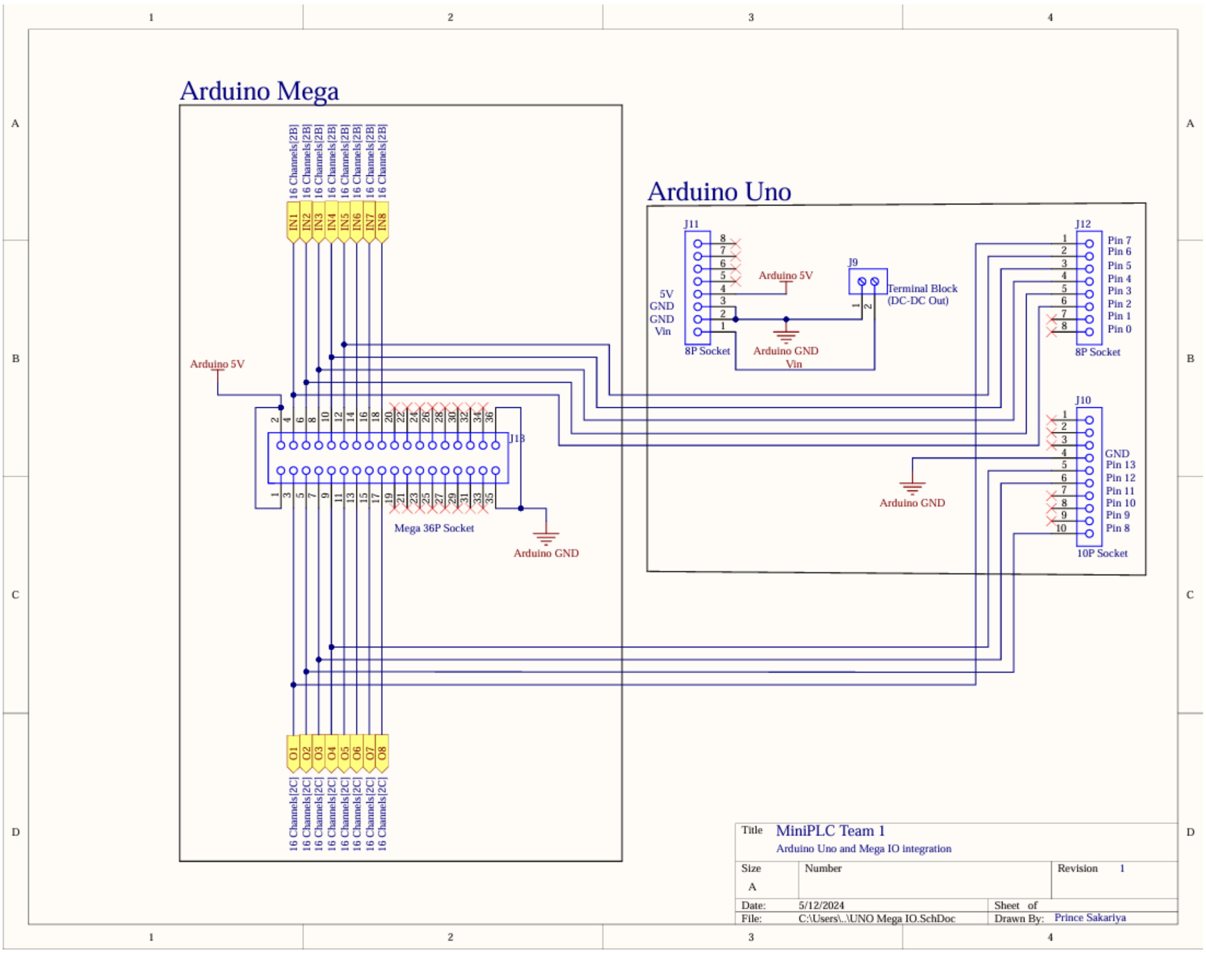

Figure 7: Schematic for I/O Integration from Arduino to Input and Output Module.

The pins are wired such that specific pins of Uno and Mega can function as either inputs or outputs. For input, you can use Mega pins 22-36 and Uno pins 2-6. For outputs, Mega pins 23-37 and Uno pins 7-13 are used. Further details can be found in table below.

[6] Open PLC Physical Addressing: https://autonomylogic.com/docs/2-4-physical-addressing/

Table 2: Physical Input Addresses for Arduino Uno and Mega.

input name on box	PCB	Mega pins	OpenPLC	Uno pins	OpenPLC
0	J1_1	22	%IX1.0	2	%IX0.0
1	J1_2	24	%IX1.1	3	%IX0.1
2	J1_3	26	%IX1.2	4	%IX0.2
3	J1_4	28	%IX1.3	5	%IX0.3
4	J1_5	30	%IX1.4	6	%IX0.4
5	J1_6	32	%IX1.5		
6	J1_7	34	%IX1.6		
7	J1_8	36	%IX1.7		

Table 3: Physical Output Addresses for Arduino Uno and Mega.

Output name on box	PCB	Mega pins	OpenPLC	Uno pins	OpenPLC
0	J2_1	23	%QX1.0	7	%QX0.0
1	J2_2	25	%QX1.1	8	%QX0.1
2	J2_3	27	%QX1.2	12	%QX0.2
3	J2_4	29	%QX1.3	13	%QX0.3
4	J2_5	31	%QX1.4		
5	J2_6	33	%QX1.5		
6	J2_7	35	%QX1.6		
7	J2_8	37	%QX1.7		

Table 2 and Table 3 also provide address information for programming the respective input and output ports in both OpenPLC software and the Arduino IDE.

These connections are made from the Arduino to the socket headers of the Mini-PLC using Dupont male-to-male jumper cables (see section 4 or refer User Manual). It is crucial to connect the cables in the correct orientation for a reliable operation of the Mini-PLC and safety of the Arduino.

PCB Layout:

The next step involves placing the components and relatively routing their connections on the PCB board. An initial layout outlining where main parts should be positioned has been developed in MCAD software Autodesk Fusion. It is crucial to define the locations of components such as banana plugs, LEDs, switches, and socket headers to ensure seamless alignment and fitting within the mechanical housing. We have designed a 2-layer PCB with a compact design of 150x160mm.

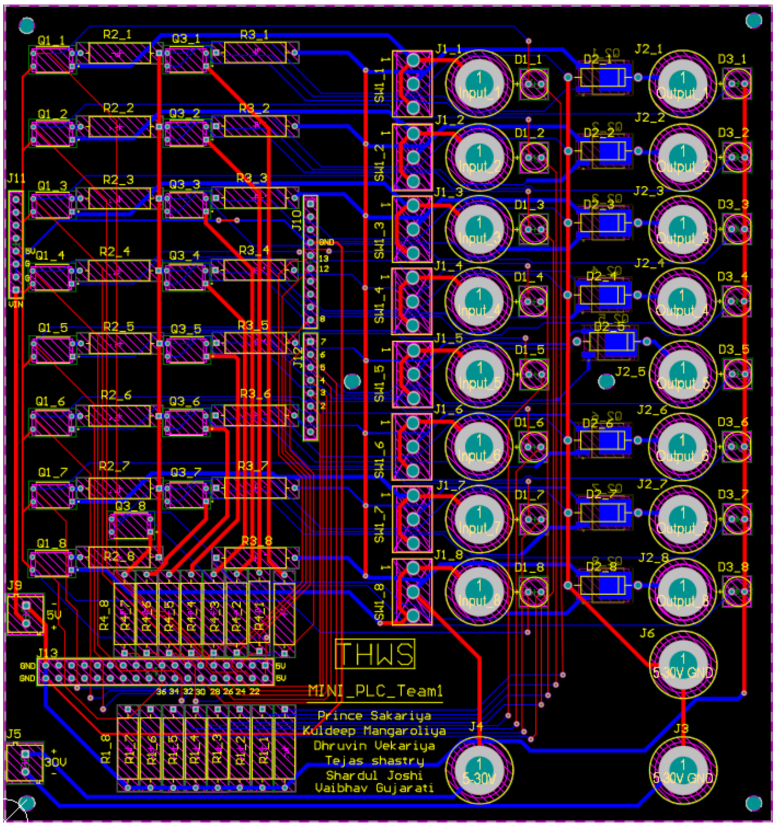

Figure 8: PCB layout of Mini-PLC.

The PCB features 8 input and 8 output modules, each equipped with female banana plugs. Various thickness settings for routing have been applied to accommodate different voltage levels, and two terminal blocks have been included to connect buck-boost converter.

Additionally, an additional common port has been added to provide ground for output devices. Red and blue lines (see Figure 8) represent connections on top and bottom traces, respectively. Six holes for M3 screw type have been created to fix PCB inside housing box.

Generation of Fabrication Outputs:

After thorough inspection of the schematic and PCB layout, the final step is to generate the Gerber and NC drill files. The format depends on the manufacturer, so it's important to consider the manufacture's capabilities to ensure a quality product.

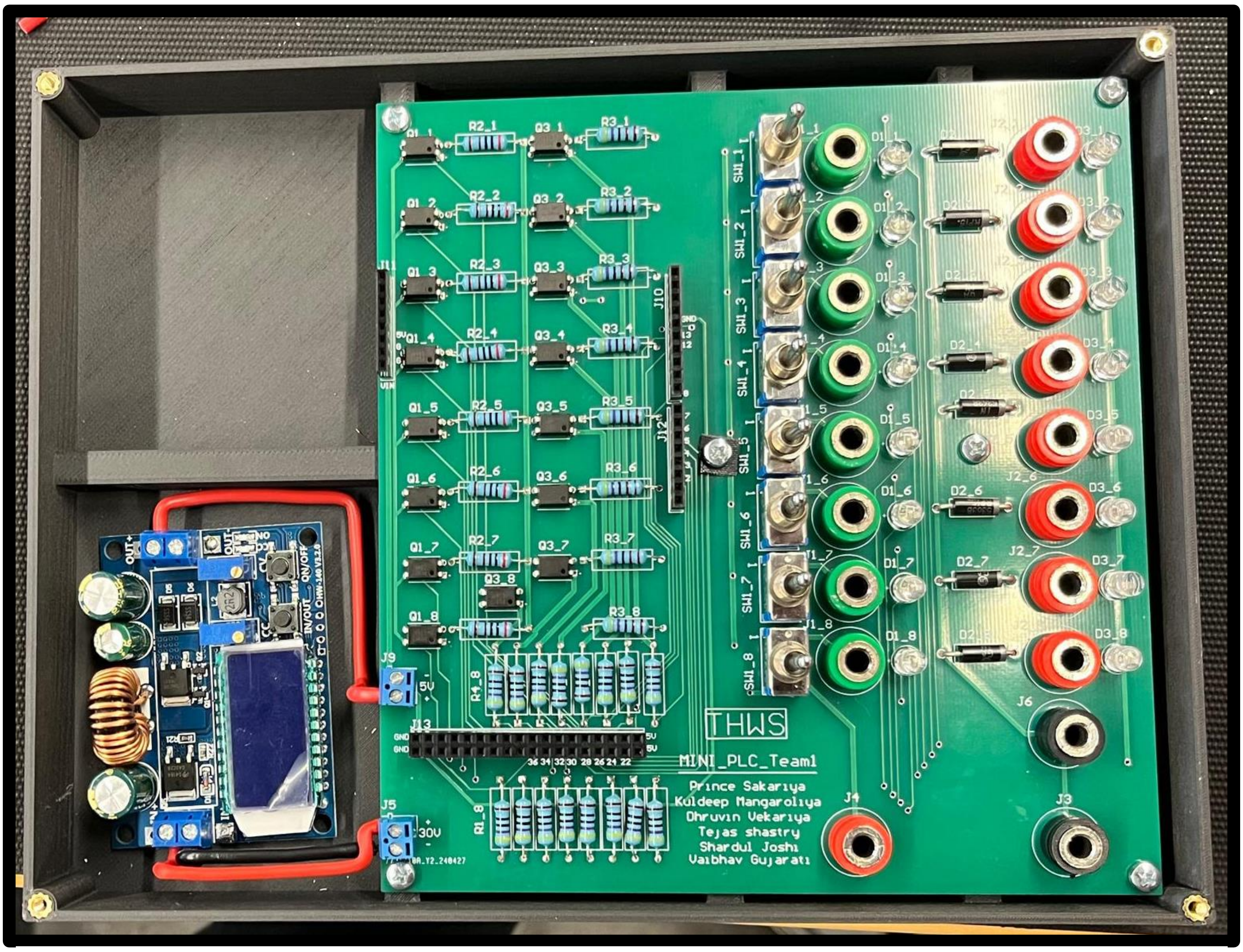

Figure 9: PCB after assembly with DC-DC Buck Boost converter.

After receiving the PCB from the manufacturer, all the components were soldered onto the board. The buck boost converter was connected using the hard wires. Finally, the PCB was mounted onto the base using M3 screws (see Figure 9).

2.5 Housing for the Electronics

Top Plate:

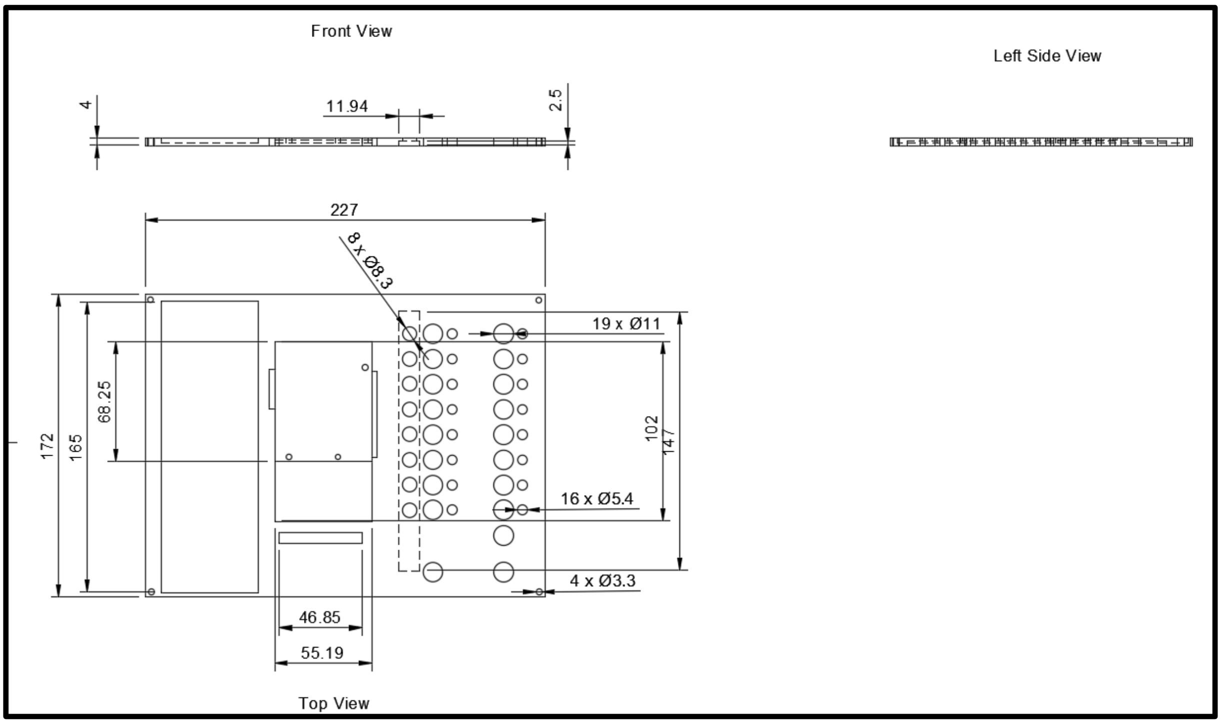

Figure 10: Design for the Top Plate (Dimensions in mm)

While keeping a minimalistic design idea in mind, Arduino board was placed on top due to easy access and top plate also showcases access to I/O female banana ports, LEDs, and on-off-mom switches.

The Arduino was set in place using plastic header which would be screwed in the top plate. Slits on top plate provide access to socket headers on PCB inside which allows users to connect Arduino to PCB using jumper wires. After the 3D printing model, additional naming stickers have been added to top plate for naming convention and corners of box has been supported by rubber cushion. The top plate is mounted on top of bottom box with four M3 screws. The dimensions of the Top plate could be seen in the Figure 10.

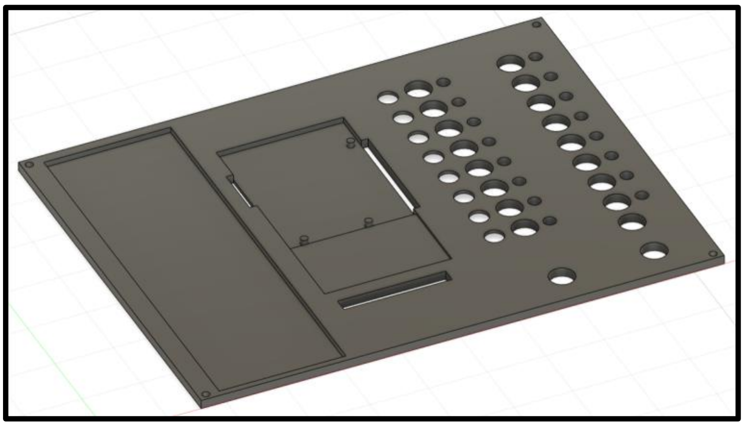

Figure 11: 3D Image of Top Plate

Housing Base:

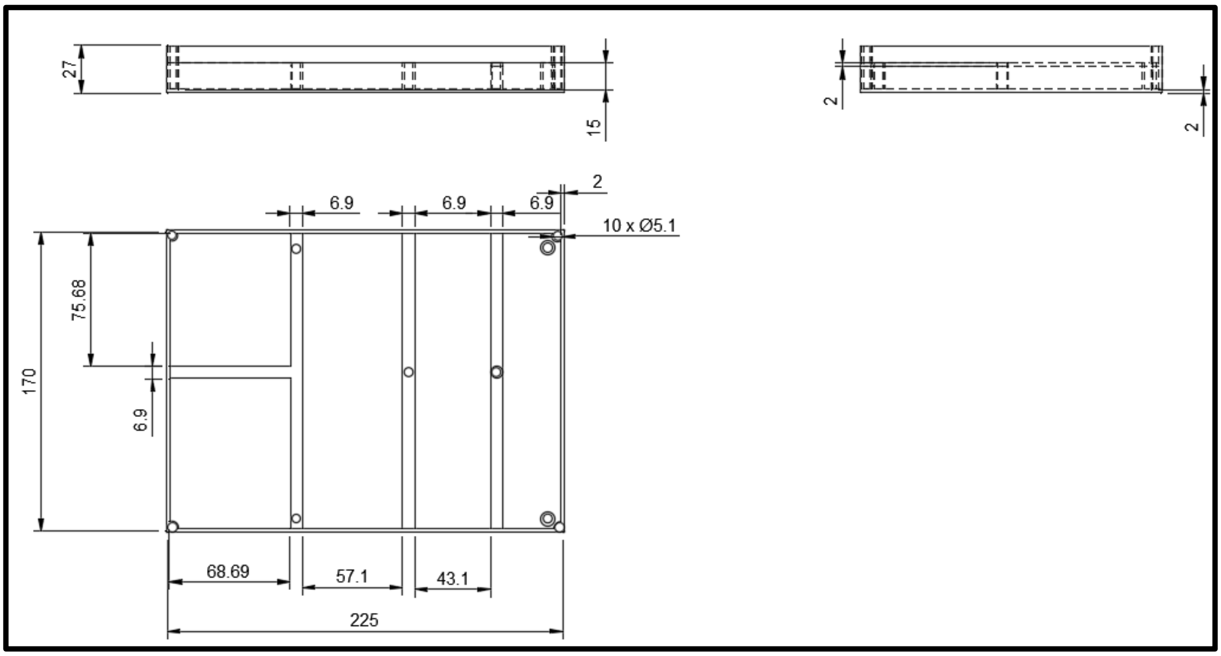

Figure 12: Design for the Housing Base (Dimensions in mm)

While designing the housing base, safe keeping of the PCB was assured by providing 4mm thickness for the walls, and abundant support beams were provided while again, adhering to the minimalistic theme. Threaded heat set inserts were used to provide threading to mount the PCB and the top plate.

The primary challenge was accommodating the PCB and its components without interfering with the support beams. This issue was addressed by strategically placing standoff beams and intelligently designing the support structure. Detailed design and dimensioning could be seen in Figure 12.

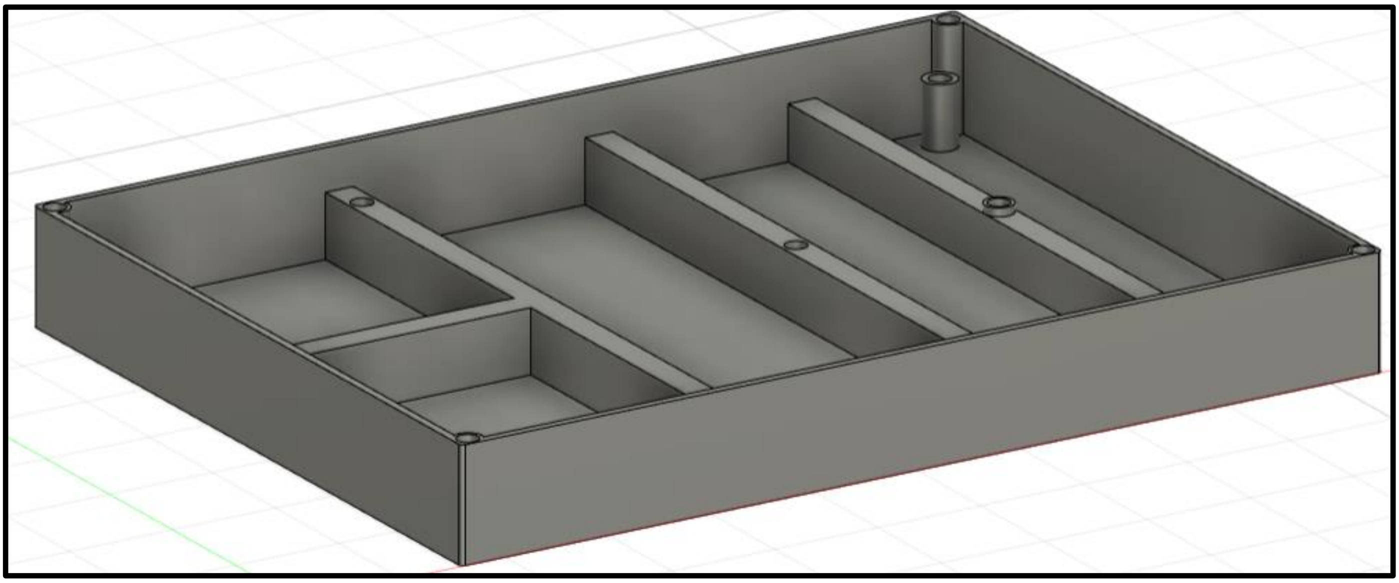

Figure 13: 3D Image of the Housing Base

4 Loading and running Mini-PLC

Loading PLC program:

The operation is to be coded using the OpenPLC software.

Complete code could be loaded from PC to Arduino board via USB Port on Arduino board.

Connecting Arduino Board:

Arduino Board can be fixed to top plat using plastic header screws.

Arduino board (Uno/Mega) needs to be powered through the ribbons provided by connecting the ribbons according to the marked labels (number 6).

When using Arduino Mega only ribbons on the bottom needs to be connected (number 4)

For Arduino Uno connect ribbons on the right side (number 7).

Connecting I/Os:

Mini-PLC could be powered from 5-30V source on Banana port (number 2 and 3). Same voltage supply is forwarded to I/O ports.

Male banana pins could be connected to I/O banana ports (number 9 and 10)

For controllable input, Manual on-off-mom switch could be used.

LEDs indicate whether I/O has received any signal.

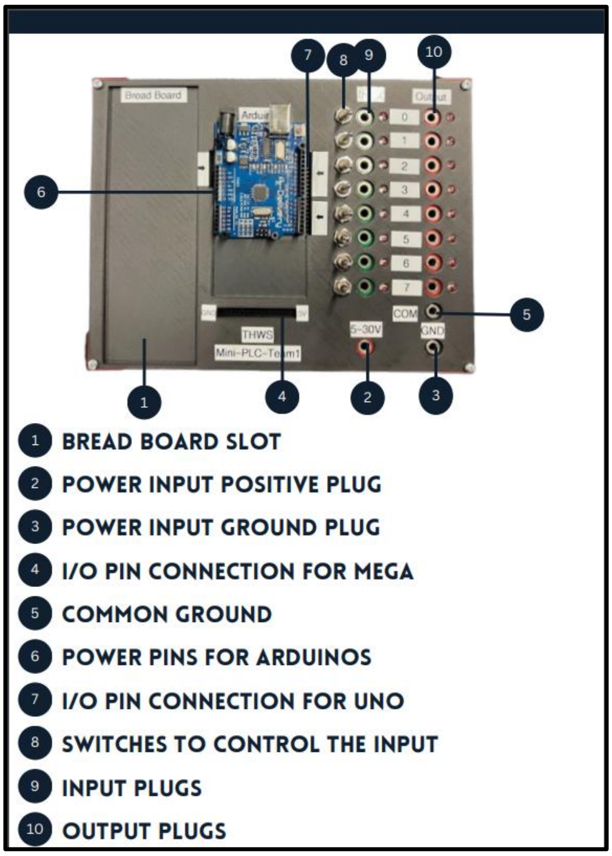

Figure 14: Top plate pointed outlook

5 Conclusion

This industrial project for developing Arduino based PLC device, many experiments and simulation has been conducted to find perfectly suitable circuits and components. After developing final product, it has been tested under various scenarios and devices. For example, with siemens relay and various laboratory devices, where it has shown remarkable performance.

Isolation provided by DC-DC buck converter, provides safety against unusual power supply. And goal of the device was only to accommodate Arduino Uno and Mega boards, but because of easily accessible jumper wires and simplicity of PCB board, one can also use other micro controller boards which are supported by OpenPLC software. As this device is specifically developed for using it with open source OpenPLC software, it is perfectly suitable for making PLC based prototypes.

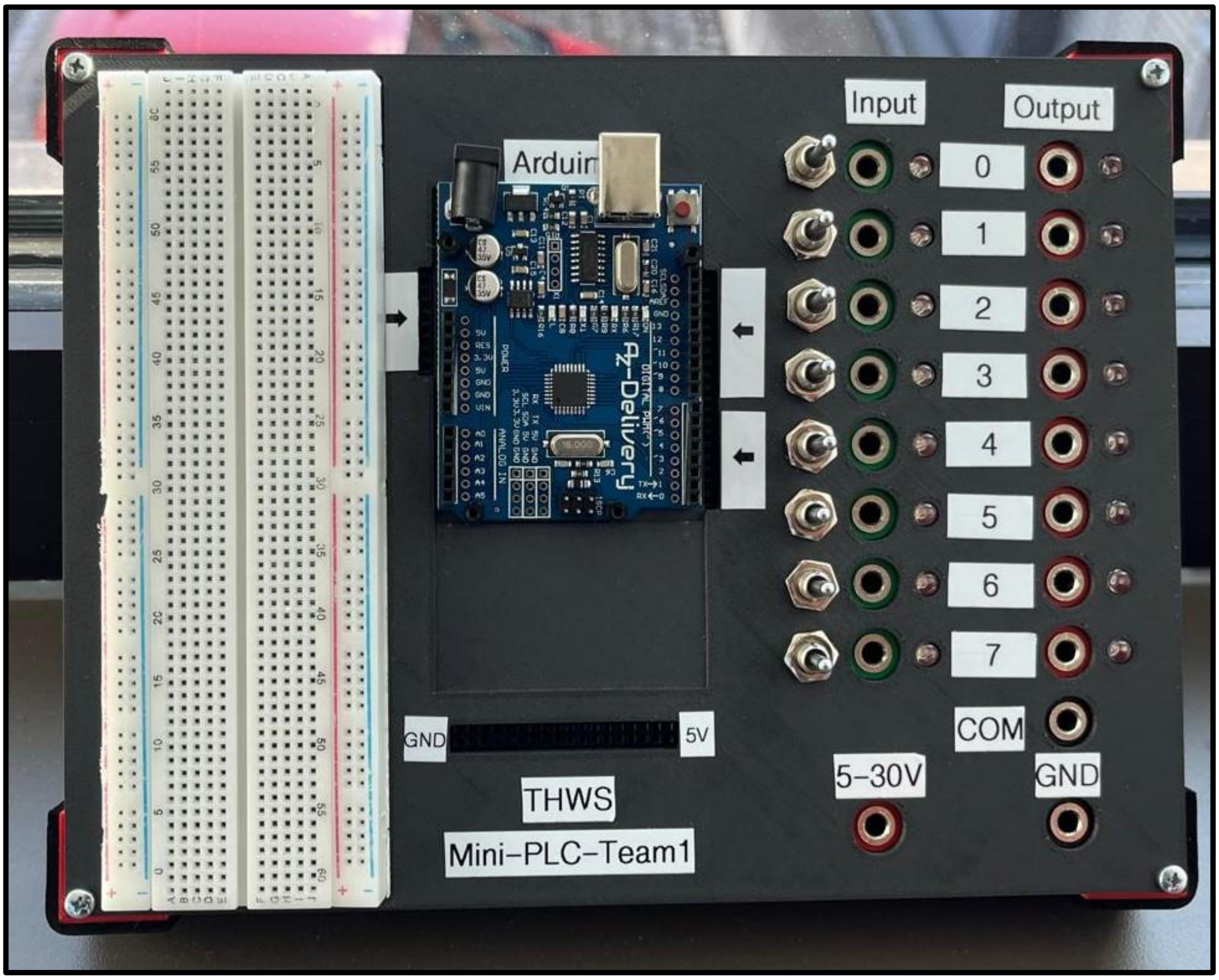

Figure 15: The Final Product

6 Appendix

To achieve the goal of avoiding lot of wires and to make the project efficient, the decision of creating a PCB was taken by the team. Multiple components were used for the input and output modules. The components were selected by researching thoroughly and understanding their documentations. The documentations for all the components selected would be listed in the appendix.

Optocoupler Input Circuits for PLCs by Lewis Loflin

https://www.bristolwatch.com/ele2/opto_input.htm

PC817 Datasheet:

https://global.sharp/products/device/lineup/data/pdf/datasheet/PC817XxNSZ1B_e.pdf

Multichannel Design Altium Designer:

https://www.altium.com/documentation/altium-designer/creating-multi-channel-design#dynamic-compilation

Sinking & Sourcing:

https://www.realpars.com/blog/sinking-and-sourcing

P-Channel MOSFET - STD26P3LLH6:

https://ptelectronics.ru/wp-content/uploads/STD26P3LLH6.pdf

Using a MOSFET with an Arduino:

https://circuitjournal.com/how-to-use-a-p-channel-mosfet-with-an-arduino

Table for Work Contributions

Participants	Project Work	Report Work
Prince Sakariya (4021094)	Input Module, Schematic Design, PCB Layout, Gerber, PCB Soldering, extensive testing.	Digital Input Module, PCB design, Appendix.
Kuldeep Mangaroliya (4020130)	Initial research, Design, PCB Layout, Gerber, PCB Soldering, extensive testing.	PCB Design, Conclusion, Powering Arduino, Introduction.
Dhruvin Vekariya (4021194)	Initial research, Input Module, Soldering, Programming, Ordering components.	Table of content, List of abbreviations.
Tejas Shastry (4021043)	Output Module, Extensive Testing, Prototype, ordering Components.	Output Module.
Shardul Joshi (4021135)	Initial research, Complete Housing design and 3D Printing, Prototype, User Manual.	Housing for the electronics, Abstract, Declaration.
Vaibhav Gujarati (4021195)	Power Module, Testing, Prototype.	Loading and Runing Mini-PLC.

Statutory Declaration

We hereby declare that this Project Work submitted, was created and written solely by Mini-PLC Team1 without any external support. Any sources, direct or indirect, are marked as such. We did not submit it elsewhere for examination purposes. I am aware of the fact that, the contents of the project work in digital form may be revised with regard to usage of unauthorized aid as well as whether the whole or parts of it may be identified as plagiarism. we do agree that our work to be entered into a database for it to be compared with existing sources, where it will remain to enable further comparisons with future projects. This does not grant any rights of reproduction and usage, however.

Wir erklären hiermit, dass diese eingereichte Projektarbeit ausschließlich von Mini-SPS Team1 ohne jegliche externe Unterstützung erstellt und verfasst wurde. Alle Quellen, direkt oder indirekt, sind als solche gekennzeichnet. Sie wurde nicht anderweitig zu Prüfungszwecken eingereicht. Mir ist bekannt, dass der Inhalt der Projektarbeit in digitaler Form im Hinblick auf die Verwendung unzulässiger Hilfsmittel überprüft werden kann sowie darauf, ob die Arbeit ganz oder in Teilen als Plagiat identifiziert werden kann. Wir sind damit einverstanden, dass unsere Arbeit in eine Datenbank aufgenommen wird, um sie mit bestehenden Quellen zu vergleichen, wo sie verbleibt, um weitere Vergleiche mit zukünftigen Projekten zu ermöglichen. Damit sind jedoch keine Rechte zur Vervielfältigung und Nutzung verbunden.

16.05.2024, Schweinfurt

Kuldeep Magaroliya

Shardul Joshi

Prince Sakariya

Dhruvin Vekariya

Vaibhav

Vaibhav Gujarati

Tejas Shastry