Eastern Mediterranean University

Department of Mechanical Engineering

Introduction to Capstone Design

MECT 411

Name of Project: *Smart - AS/RS*

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ABSTRACT

With the adoption of Just in time systems and low warehouse staff volumes, it is essential to reduce order cycle times to keep product throughput stable. Delays and incorrect orders due to human errors highly affect this and lead to decreased efficiency and profit losses. The ongoing developments in Industry 4.0 and machine to machine communication mitigate these issues. This project achieves this through the implementation AS/RS with RFID. AS/RS provides low order cycles and high throughput with the benefits of high-quality control standards, safety and increasing products per meter square in warehouses. RFID (Radio-frequency identification) automatically identifies and tracks objects, eliminating incorrect product orders. Research into AS/RS is still ongoing and will be implemented into various industries in the future.

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Table 0-1 Symbols and Abbreviations

Abbreviation	Full form
3D	Three Dimensional.
PLA	Polylactic acid (referring plastic).
ABS	Acrylonitrile Butadiene Styrene.
DOF	Degree(s) of Freedom.
ROI	Return on Investment.
Etc.	Etcetera.
SCARA	Selective Compliance Articulated Robot Arm.
CR-10S	Creality 10S.
OEM	Original Equipment Manufacturer.
FMEA	Failure Mode and Effects Analysis.
RPN	Risk Priority Number.
PLC	Programmable Logic Controller.
API	Application Program Interface.
CMM	Coordinate Measuring Machine.
QR code	Quick Response Code.
ISO	International Organization for Standardization.
PDF	Portable Document Format.
TRNC	Turkish Republic of Northern Cyprus.
AS/RS	Automated Storage and Retrieval System.
DC	Direct Current.
STL	Stereo lithography file.
VLM	Vehicle Lift Module.
DFMA	Design for Manufacturing and Assembly.
SBS	System Breakdown Structure.
RBD	Reliability Block Diagram
QR	Quick Response
Vref	Reference Voltage
RFID	Radio Frequency Identification
FDM	Fusion Deposition Modeling
M2M	Machine-To-Machine

ROS	Robot Operating System
BDS	Berkeley Software Distribution
CALT	Calibrated Accelerated Life Testing
API	Application Programming Interface

CHAPTER 1 - INTRODUCTION

1.1 Detailed definition of the project

Industry 4.0 is the current trend of automation and data exchange in manufacturing technologies. It includes cyber-physical systems, the Internet of things and cloud computing. Industry 4.0 creates what has been called a “smart factory” (Industry 4.0, 2020). This project is a small-scale model of an Automated Storage and Retrieval System (AS/RS) that demonstrates how a full-scale automated warehouse can be operated. It deploys RFID code system and communication between raspberry pi and Arduino which provides automation without the interference of humans. Now since the RFID sensor is used, which will be communicating with the raspberry pi to make decision for the location of each delivery package, it can be said that this system also includes machine to machine communication. Figure 1.1-1 shows a full scale AS/RS render.

Figure 1.1-1 AS/RS (Cribley, 2011).

Automated storage and retrieval systems are most commonly used in manufacturing and distribution facilities. AS/RS are computer- and robot-aided systems that can retrieve items or store them in specific locations. The system is usually comprised of predefined locations where machines can follow established routes to get items. As long as everything is stored in its proper location, these systems help to speed up manufacturing and shipping tasks. Typically, automated storage and retrieval systems are used when high volume loads must be moved rapidly and accurately (Allen, 2020).

Basically, there are two different types of automated storage systems. First is the rack system with mechanized or automated crane to store/retrieve loads. This can be seen in the figure 1.1-1. Second is the carousel storage system, it consists of oval conveyor system with bins to contain individual items as shown in figure 1.1-2. This project has been done with the rack system with automated crane.

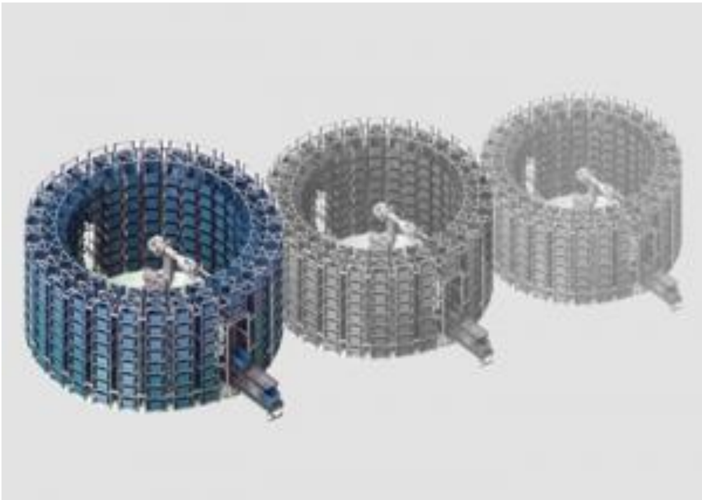

Figure 1.1-2 Carousel S/R system (Carousel racking)

1.2 Significance of the project

This project could be used to demonstrate how an AS/RS works to potential investors and how such system could benefit their operations. Material handling is the most crucial part to an industry. The protection, movement, control of materials, and end products throughout the process of manufacturing, disposal, distribution, warehousing, and storage comes under material handling. This project makes the process easier by autonomously handling the materials. Using automation in material handling can benefit a company vastly in many different aspects. It may lower the labor cost as less labor is required for the operations. It can also improve the floor space utilization since the AS/RS system can utilize the ceiling height of the facility. Since the system is autonomous, it has a perfectly designed shape of picking and dropping, and hence this will increase the accuracy of delivery which also reduces product damage. This system can also eliminate the risk of handling of hazardous materials such as chemicals or heavy materials, hence making the system safer for the environment (Nilkamal, 2018).

1.3 Detailed project objectives

1. Design for cost:

It is important to estimate the cost of the project early on in the design process. That is why, this project will mostly be using components available in the local market and would not require manufacturing to avoid any cost that might not be obvious in the early stages.

2. Design for availability:

When doing this project in Turkish Republic of Northern Cyprus, the availability of materials is a major issue. Hence the design was a bit altered to meet the requirements of the project keeping the availability of materials in mind.

3. Design for manufacturability:

The components used for manufacturing this product are mostly off the shelf components for maximum compatibility and to avoid waste.

4. Design for reliability:

The product will be designed in such a way that it maintains its quality over time. This will be discussed further on in the report.

1.4 Detailed project constraints

1. Economic: The design should be economically viable. Preferably, around $1000.
2. Availability: The product must be designed by employing materials/components available in the local and online market.
3. Manufacturability: The product must be easily manufactured, requiring only assembly and simple machining.

1.5 Report Organization

This report will mention all the details and activities performed by the capstone team during the semester period. This report has been divided into five different chapters. First chapter gives the general information about the project in details. The second chapter gives the literature review about the project. Then the third chapter will discuss the designing and analysis performed and will also be giving the cost analysis. The fourth chapter will mention the manufacturing plans and processes in quite details. In the end, the fifth chapter, will be testing plans for the project according to its objectives and the engineering standards.

CHAPTER 2 - LITERATURE REVIEW

2.1 Background information

The technology now known as Automated Storage and Retrieval System (AS/RS) was originally developed by Dematic's predecessor Demag, and its foundation of innovation lives on in today's modern high-bay warehouses and efficiently controlled material flows in industry and logistics (Clark, 2019). AS/RS are robots that store and retrieve objects from predetermined positions. They have been a fixture within the global supply chain for about sixty years. These systems speed up warehousing and shipping operations especially in high volume applications (Allen, 2020). These systems have lots of advantages that increases efficiency:

- "Maximizing available storage space in existing structures, avoiding off-site storage and expansions.
- Minimizing overall building footprint up to 50% versus conventional warehouses.
- Reducing energy costs by 40% in cooler environments.
- Reducing labor and product damage costs.
- Increasing inventory accuracy and customer service." (Automated Storage and Retrieval Systems)
- Improved product security for premium inventory. (Romaine, 2020)

2.2 Concurrent solutions

There are majorly six different types of Automated Storage and Retrieval Systems (AS/RS). The two main varieties, Unit-Load AS/RS and Mini-Load AS/RS, are majorly used in industries. The types of AS/RS are listed below:

1. **Unit-Load AS/RS (Fixed aisle and movable aisle):**

Unit-load AS/RS as shown in figure 2.2-1, is used to move exceptionally large and heavy objects ranging from 1,000 to 5,500 pounds. They consist of narrow aisle racks, which can extend to the heights of more than 100ft and which house pallets of product and inventory. Unit-load AS/RS is a useful option when pallet-level storage is limited, and quick retrieval is important. (Romaine, 2020)

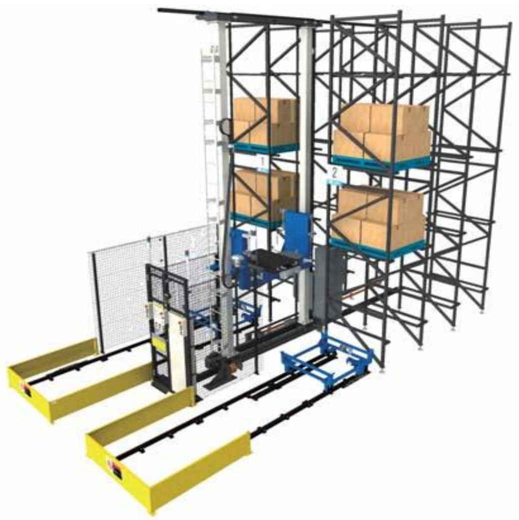

Figure 2.2-1 Unit-Load AS/RS (Romaine, 2020)

2. **Fixed-Aisle Unit-Load AS/RS Crane:**

Fixed-aisle unit-load AS/RS, as shown in figure 2.2-2, has pallet racks that are arranged with narrow aisles in between. A crane moves between these aisles vertically and horizontally to retrieve and store products. The crane is fixed to a single aisle of pallets. (Romaine, 2020)

Figure 2.2-2 Fixed aisle AS/RS (Romaine, 2020)

3. **Moveable-aisle unit load AS/RS:**

They are similar to fixed-aisle unit-load AS/RS. It consists of a crane moving between narrow aisles of pallets along a track. The difference is that it is not fixed to any aisle, as shown in the figure 2.2-3. This allows a system to access multiple places thus more work areas. (Romaine, 2020)

Figure 2.2-3 Movable aisle AS/RS (Romaine, 2020)

4. **Mini-load AS/RS:**

A mini-load AS/RS is shown in figure 2.2-4. They handle smaller loads up to 70 pounds, in totes, trays or cartons. They are suited for operations that require a large storage but was small floor area. (Romaine, 2020)

Figure 2.2-4 Mini-load AS/RS (Romaine, 2020)

5. **Shuttle-based AS/RS:**

Shuttle-based AS/RS, as shown in the figure 2.2-5, moves products through a shuttle that moves on a track. When an item is needed, the shuttle moves to the location of the item and retrieves the tote that contains the item. The shuttle will then take the tote station or move it to a conveyer. (Romaine, 2020)

Figure 2.2-5 Shuttle based AS/RS (Romaine, 2020)

6. Carousel-based AS/RS:

"Carousel-based AS/RS, as shown in the figure 2.2-6, consist of bins of product or inventory which rotate continuously along a track. When the operator requests a particular item, the system will automatically rotate so that the appropriate bin is accessible so that the item can be picked. An integrated light will indicate to the picker which carousel, shelf, and item to pick." (Romaine, 2020)

Figure 2.2-6 Carousel-based AS/RS (Romaine, 2020)

7. Vertical Lift Module (VLM)

"A vertical lift module (VLM), as shown in the figure 2.2-7, is an enclosed system consisting of an inserter/extractor in the center and a column of trays on either side. It is a form of goods-to-person technology. Trays may either be fixed or dynamic. In fixed systems, individual trays will always be returned to the same location; in a dynamic system, where individual trays are stored will vary." (Romaine, 2020)

Figure 2.2-7 Vertical lift module AS/RS (Romaine, 2020)

a. Micro-Load Stocker

"A Micro-Load Stocker, as shown in the figure 2.2-8, provides discrete or individual totes or carton storage and retrieval. It is ideal for buffering, sequencing, and point-of-use items in a high-density footprint." (Romaine, 2020)

Figure 2.2-8 Micro-Load stocker AS/RS (Romaine, 2020)

2.3 Comparisons of the concurrent solutions

The table 2-1 below shows the comparison between the different variants of AS/RS and lists all the differences.

Table 2-1 Comparison of concurrent solutions (Romaine, 2020)

Types	Differences
Fixed-Aisle Unit-Load AS/RS Cranes	• Large loads • Fixed to aisle
Movable-Aisle Unit-Load AS/RS Cranes:	• Large loads • Not fixed to aisle
Mini-Load AS/RS Crane:	• Smaller loads • Not fixed to aisle • Moves totes and cartons instead of pallets
Mini-Load AS/RS Shuttle:	• Moves on a track
Carousel-based AS/RS:	• Structure spins until item is in position
Vertical Lift Module (VLM)	• Item directly delivered to operator

2.4 Engineering standards of the concurrent solutions

In this chapter, the table 2-2 will show the key standards of the concurrent solutions to this project, used by the companies in order to build their AS/RS robots.

Table 2-2 Key standards of the concurrent solution

Application Area	Standard	Remark
Quality management System	ISO 9001: 2008	Quality of the system.
Information Technology	iso 18001: 2004	Radio frequency identification for item management. Application requirements profiles.
Safety	OSHA 18001: 2007	Health and safety of machinery, function and workers.
Engineering	UNE EN ISO 3834-2: 2006	Welding certification.
	UNE EM ISO 14713-1	Galvanized steel corrosion resistance certificate.
	EN 13501-1: 2007	Galvanized steel reaction to fire.

CHAPTER 3 - DESIGN and ANALYSIS

3.1 Proposed/Selected design

In this chapter, the report will describe the proposed design which was done over the summers of 2020, and then it will demonstrate how some designs evolved due to the issues faced or just to make the system better. In the end, it will illustrate the final selected design of this project. A system breakdown structure flowchart has been shown in the figure 3.1-1 below.

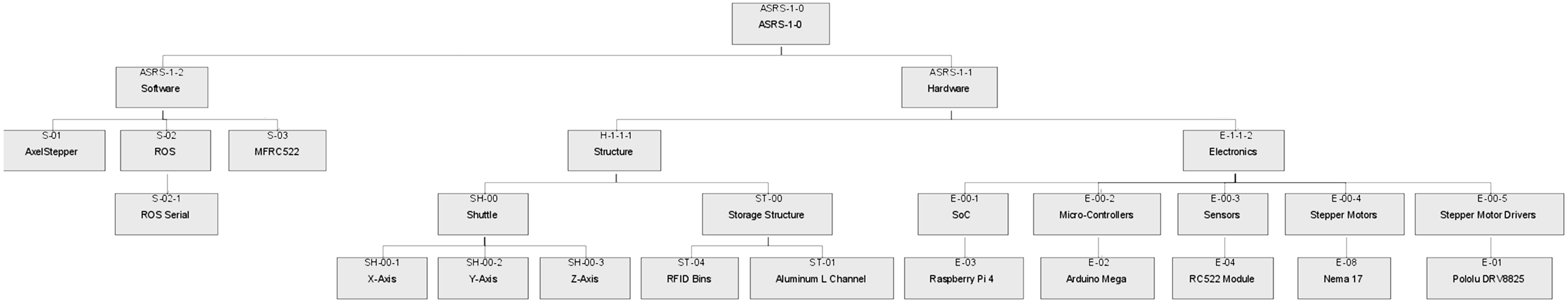

Figure 3.1-1 System Breakdown Structure

3.1.1 Proposed Design

The figure 3.1-2 shown above is the selected design for a Mini-Load AS/RS. The shuttle of the AS/RS model will be manufactured by using the 3D printer with the ABS filament and the storage rack will be made of Aluminum extrusions. The shuttle designed for most general type of pallet variables. This automated storage and retrieval system will be able to work flexible temperature and environment conditions. The three major parts of this AS/RS system involves pallet system, Controller, and storage rack.

Figure 3.1-2 Design of the AS/RS

3.1.1.1 Pallet System

Pallet system is the main electrical and mechanical part of the automated storage and retrieval systems. It moves with a 3 degree of freedom (X, Y and Z) and each degree has its own mechanical systems and motor.

A. Motors proposed for Pallet System

Servo Motors: A servomotor is a rotary actuator or linear actuator that allows for precise control of angular or linear position, velocity and acceleration. It consists of a suitable motor coupled to a sensor for position feedback. It also requires a relatively sophisticated controller, often a dedicated module designed specifically for use with servomotors.

Geared DC Motors: Geared DC motors can be defined as an extension of DC motor which already had its insight details demystified here. The gear assembly helps in increasing the torque and reducing the speed (RPM) (Motors and Geared motors, 2016). Using the correct combination of gears in a gear motor, its speed can be reduced to any desirable figure. This concept where gears reduce the speed of the vehicle but increase its torque is known as gear reduction.

Stepper Motors: A stepper motor, also known as step motor or stepping motor, is a brushless DC electric motor that divides a full rotation into a number of equal steps. The motor's position can then be commanded to move and hold at one of these steps without any position sensor for feedback (an open-loop controller), as long as the motor is carefully sized to the application in respect to torque and speed. In this project, two Nema 23 stepper motors will be used to operate X and Y axis of the pallet system and Nema 17 stepper motor for Z axis (Shuttle). The advantages of these motors are as follows:

1. They do not require feedback. The engine is controlled in an open loop.
2. The motor can take the desired position with minimum error.
3. They can be controlled through PLC or Microprocessor elements.
4. They are economical and easily available in local markets.
5. Since they have a simple mechanical structure, they do not require maintenance.
6. They can be operated several times without causing damage to the system they are applied to.

B. **Controller Proposal for the AS/RS System**

Arduino: Arduino is a platform used for building electronic projects. Arduino consists of both, a physical programmable circuit board and a piece of software, or IDE that runs on your computer, used to write and upload computer code to the physical board.

Raspberry Pi: The Raspberry Pi, as shown in the figure 3.1-3 below, is a series of small single-board computers.

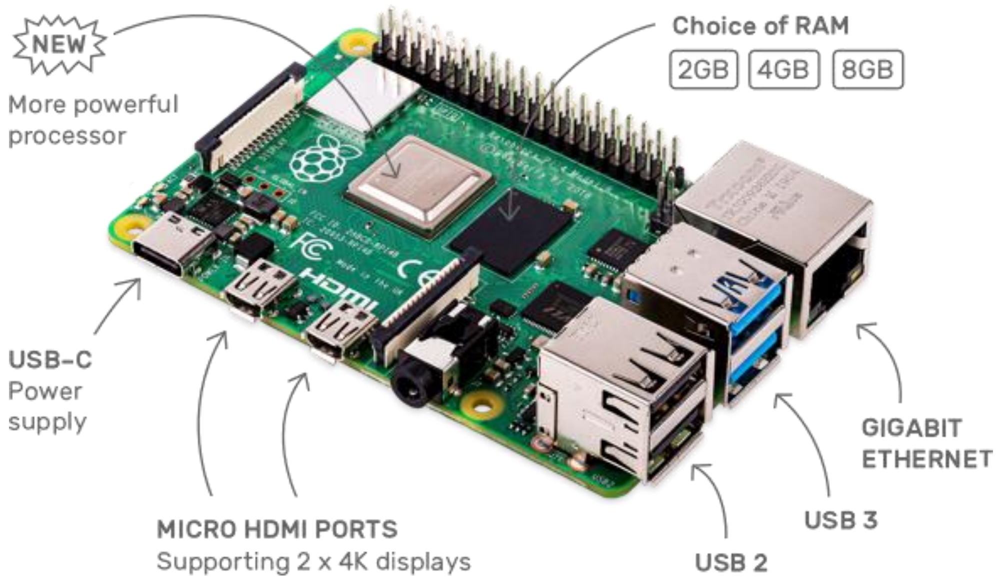

Figure 3.1-3 Raspberry Pi 4 (Rasbberry Pi 4, n.d.)

PLC: A programmable logic controller (PLC) or programmable controller is an industrial digital computer which has been ruggedized and adapted for the control of manufacturing processes, such as assembly lines, robotic devices, or any activity that requires high reliability, ease of programming and process fault diagnosis.

3.1.1.2 PLC

A Programmable Logic Controller, or PLC, is a ruggedized computer used for industrial automation (PLC, 2008). These controllers can automate a specific process, machine function, or even an entire production line.

A. PLCs proposed for AS/RS System

There are many types of PLC's produced by companies in the market. The PLC by each company has its advantages and disadvantages compared to each other. While selecting the suitable PLC for AS/RS project, primarily the components of the pallet system mechanism controlled and listed also working standards determined before buying PLC. The results of the PLC selection are reached by considering the following conditions:

1. The status of the PLC output must be relay and transistor
2. PLC input and output numbers must meet the mechanism of the pallet system needs.
3. Must have an easy programming feature.
4. It must have communication protocols and communication facilities.
5. Sufficiency of warranty conditions

According to conditions and standards listed above, the companies and their PLC products with their properties are indicated below:

1- Gemo AR1-A PLC

A. Programmable with the ladder system.
B. Ladder operator with graphic infrastructure working free of charge in computer environment.
C. 12 input and 8 output.
D. 16 relays.
E. 10ms scanning time.

F. Possibility to design, control and transfer programs with a computer.

G. 100-240V AC and 18-32V DC source supply options.

H. Power consumption less than 12V A-8W.

I. Possibility to work at 0-50 ºC temperatures.

This PLC with the features stated in the catalog (PLC, 2008), although it is suitable in terms of price and design, it is not preferred for this project because of weak infrastructure, scanning time is higher than other products on the market and efficiency in the desired connections. A Gemo AR1 PLC is shown in figure 3.1-4

Figure 3.1-4 Gemo AR1-A PLC (PLC, 2008)

2- Siemens Kit 12/24RCE PLC

a. Simple setup, design and operation.

b. Physical advantages and solid structuring.

c. Basic and mixed automation control.

d. Low price, good performance.

e. Strong communication (profibus cable).

f. Possibility to command separately for all users.

g. 12 input and 12 output

h. 5ms scanning time.

i. Possibility to work at 0-70^{o}C temperatures.

As the given properties in Siemens website (Siemens, nd) the features and price of this PLC are satisfying with this project, also there are additionally two more criteria, that is why this PLC is better than the other PLC’s. Moreover, these are also available in Turkey and it comes with software and Kit. This Siemens PLC Kit is shown in the figure 3.1-5.

Figure 3.1-5 Siemens PLC kit (PLC Controllers, n.d.)

3.1.1.3 Storage Rack

“Rack or racking, one of the fundamental tools in material handling industry, is a steel structure composed of two or more upright frames, beams, and connectors for the purpose of supporting materials in storage” (Rack, n.d.). Usually they are assembled by the mechanical ways like welding, bolting or clipping.

a) In this AS/RS model aluminum T-slots can be used to build storage rack and for flexible manufacturing, clips can be used to reorganize the rack system. The T-slots can also be used to build up the X and Y axes beams.

b) This AS/RS system can also use T-slots for building the rack and use drilling of the rods in order to build up the rack. With 20x20 T-slots for X and Y axes beams

c) L-slot beams could be used by drilling to make up the rack and with 20x40 T-slots for X and Y axes beams.

3.1.1.4 Scanning technology

A. Barcode scanner

It is a machine-readable representation of numbers and characters. A bar code scanner and barcode can be used for calling the delivery boxes. It focuses a light beam on a barcode and the photodetection reads the reflected code. A barcode scanner is shown in figure 3.1-6.

Figure 3.1-6 Barcode scanner

B. RFID scanner

A Radio Frequency Identification technology, as shown in the figure 3.1-7, RFID for short is a read-write scanning technology. RFID is similar to barcoding in that data from a tag or label are captured by a device that stores the data in a database. RFID, however, has several advantages over systems that use barcode asset tracking software. (RFID)

Figure 3.1-7 RFID scanning system (RFID scanner)

3.1.1.5 Control box

Electrical control box is to be used in this project for the power supple and contactor to connect the emergency switch and ON/OFF button.

3.1.2 Selected Design

A. Selected motors:

After a good amount research and meeting the team decided to use stepper motors for all the three axes (X, Y and Z). In this project, three Nema 17 stepper motors are used to operate X, Y and Z axis of the crane system. These motors are shown in the figure 3.1-8. The advantages of these motors are:

1. They do not require feedback. The engine is controlled in an open loop.
2. The motor can take the desired position with minimum error.
3. They can be controlled through PLC or Microprocessor elements.
4. They are economical and easily available in local markets.
5. Since they have a simple mechanical structure, they do not require maintenance.
6. They can be operated several times without causing damage to the system they are applied to.

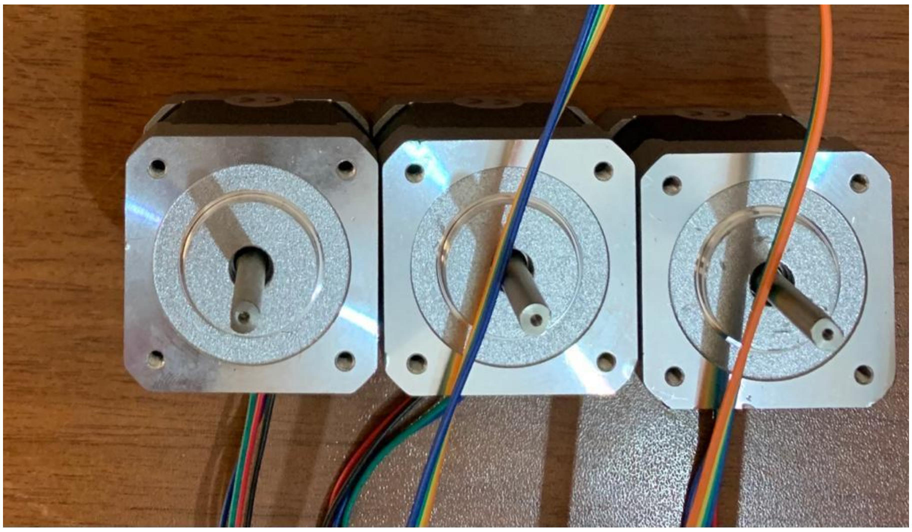

Figure 3.1-8 Stepper motors

B. Selected Controller

Since this project is done by university undergraduate students so the cost is one of the main aspects to keep in mind. Hence when making this decision, the team didn't have to work a lot on it and simply chose Arduino with ramps 1.4 internally connected with raspberry pi 4. The team excluded PLC because of its prices plus the lack of experience using it. This connection of Arduino and Ramps 1.4 is shown in the figure 3.1-9 below.

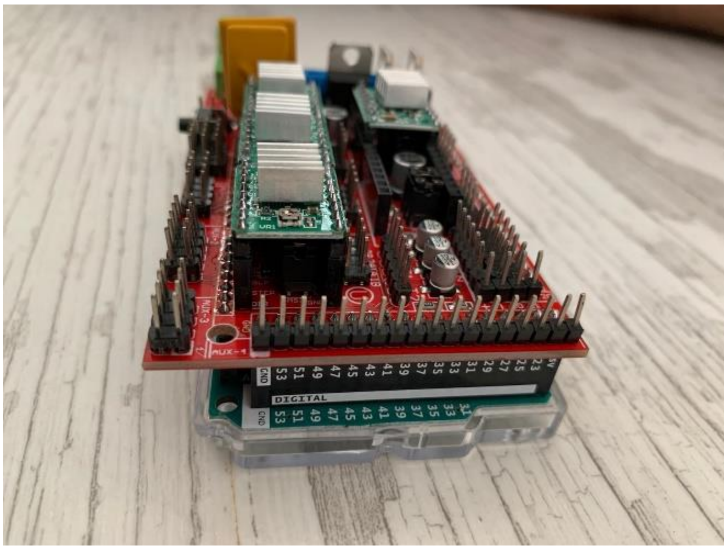

Figure 3.1-9 Arduino and Ramps 1.4

C. Selected Storage Rack Design

To build up the rack, the L-slot aluminum rods, as shown in figure 3.1-10, are selected with 20x40 T-slot aluminum for the X and Y axes beams.

Figure 3.1-10 L-slot aluminum bars

D. Selected Scanning Technology

Choosing between RFID and Barcode was a challenge so a comparison table was made to mark the differences between RFID and barcode scanning technology, this table 3-1 is shown below.

Table 3-1 Comparison between barcodes and RFID (Groover, 2007)

Comparison	Bar Codes	RFID
Technology	Optical	Radio frequency
Read-Write capability	Read only	Read-write availability
Memory capacity	14-16 digits (linear)	96-256 digits
Line-of-sight reading	Required	Not required
Reusability	One-time use	Reusable
Cost	Very low	Approximately 10x cost of bar code
Durability	Susceptible to dirt and scratches	More durable in industrial environment

A Radio Frequency Identification technology, RFID for short has been selected to perform this project. Hence its read-write depending on the radio frequency. Hence this makes it more useable than the QR codes. The RFID scanner and cards are shown in the figure 3.1-11 below.

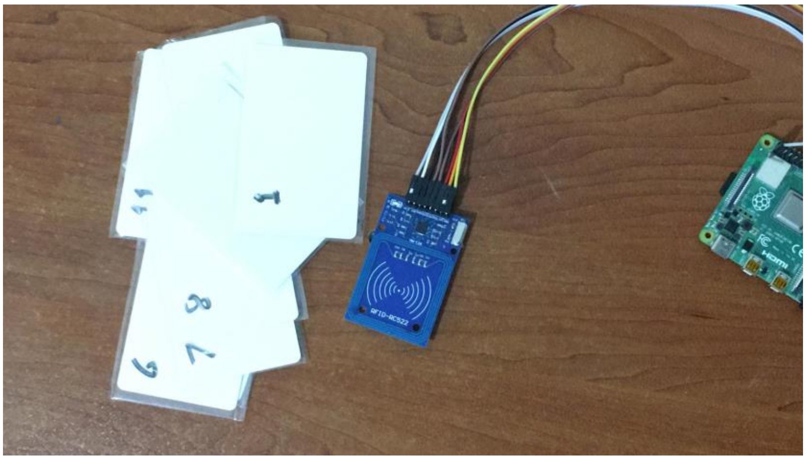

Figure 3.1-11 RFID Scanner and Cards

3.1.2.1 Control box

Electrical control box with standard emergency switch and ON/OFF switch, carrying a power supply and contactor. This has been illustrated in the figure 3.1-12 and 3.1-13.

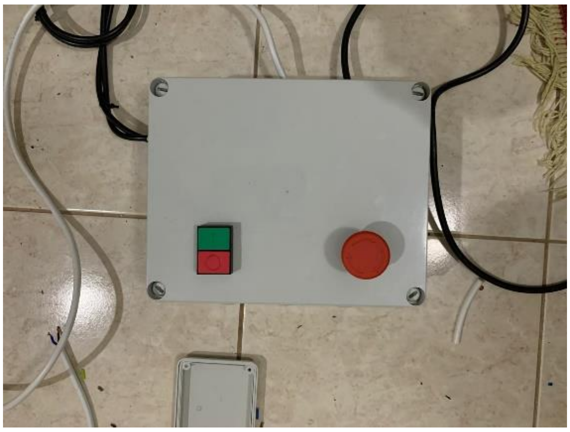

Figure 3.1-12 Control box exterior

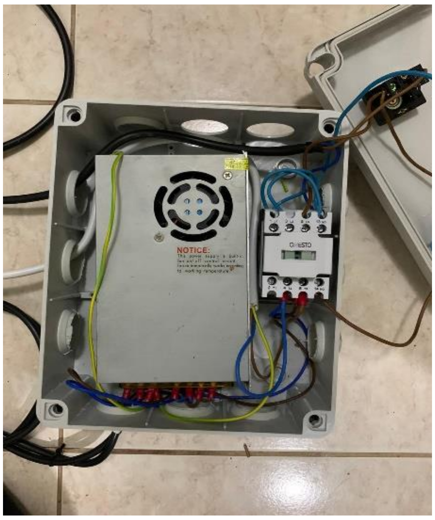

Figure 3.1-13 Control Box interior

3.1.3 Design configuration

Configuration design is a type of conceptual design activity in which physical systems are synthesized from a set of predefined components that can be combined only in certain ways.

3.1.3.1 Racking system

Configuration 1:

When the design was being made for the first time, these aluminum beams were selected in order to build up the racking system. But later on, it was found out that the beams were not strong enough to hold it together, hence there were increased inefficiencies and inaccuracies. After a meeting, the team figured that this happened because of too many holes and less thickness, which decreased the strength of the material. This is shown in the figures 3.1-14 and 3.1-15.

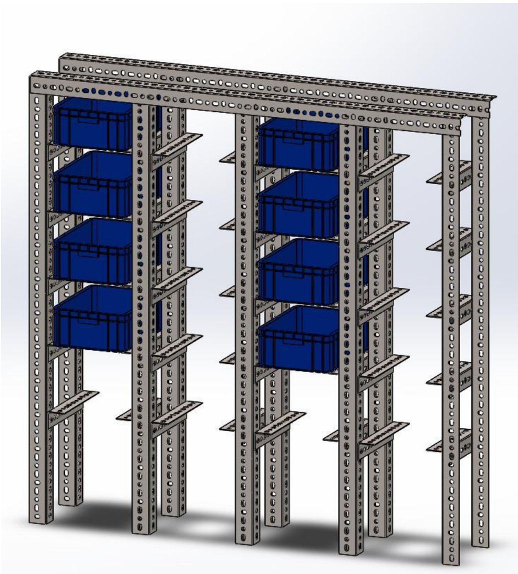

Figure 3.1-14 Primary racking design

Figure 3.1-15 L-Slot aluminum beams

Configuration 2:

To overcome these issues, the team decided to replace these aluminum beams with new beams without any pre-made holes. The idea was to get the beams and drill it in the campus workshop by self. Due to less holes, this design makes the whole system looks more presentative and attractive. So, these issues were solved and the new design and beams are shown in the figure 3.1-16 below.

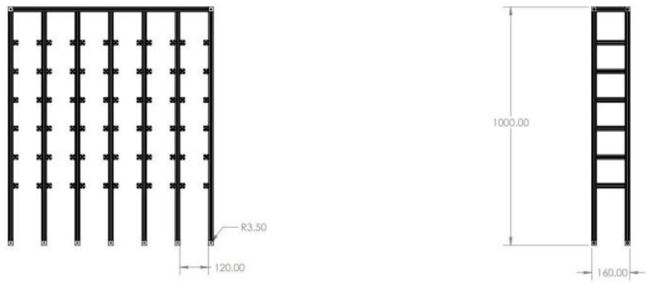

Figure 3.1-16 Updated racking design

3.1.3.2 Shuttle System

Configuration 1:

This model of a shuttle system was first designed which would have worked finely as it can be seen in the figure 3.1-17, the model did not work as expected. There were some minor errors which caught the eyes while in the testing stages. The problems occurred were that the distance the shelf could move was not as much as required. Upon that, since the two pulleys were 3-D printed and were unable to rotate, this created an issue of the belt slipping steps. Hence the system did not work perfectly so the team had to make some changes in the shuttle system.

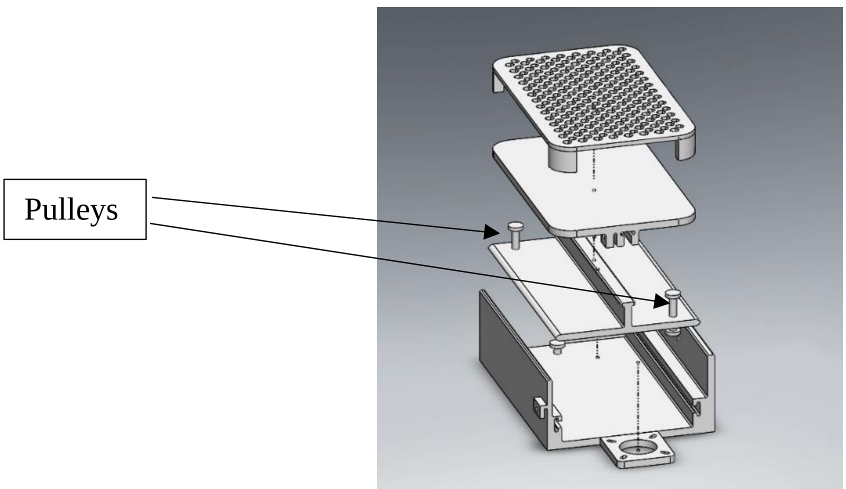

Figure 3.1-17 Shuttle System

Configuration 2:

Now to overcome the issues faced in the first configuration, the design was altered a bit to increase the maximum distance traveled by the shuttle and to avoid the slipping and loosing of belt due to the pulleys. As shown in the figure 3.1-18, a hole was drilled at the center of the base and a rotating pulley was added. This fixed the problems related to slipping and loosing of the belt. Upon that the first level was cut down to achieve maximum distance.

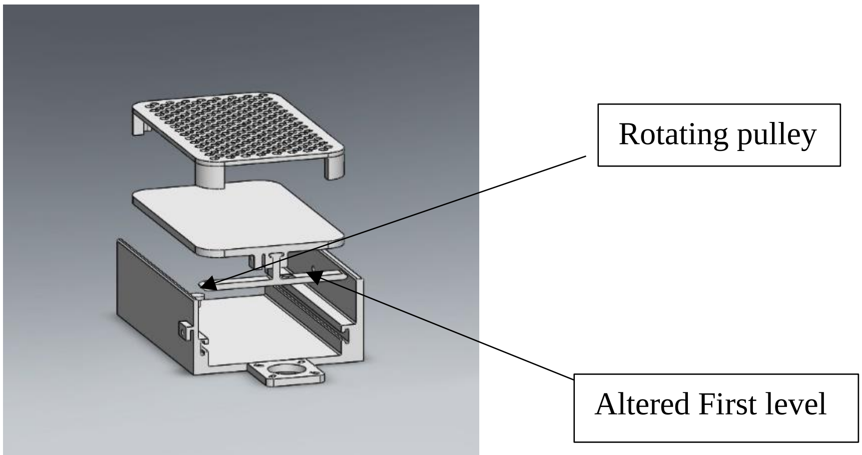

Figure 3.1-18 Redesigned Shuttle System

Configuration 3:

Since the shuttle was too close to the Y axis extrusion, so the idea came up to a team member, and it was measured and analyzed by the team and then the part was designed and added to increase the distance between the Y axis and the shuttle system. The new Part E is shown in the figure 3.1-19 below.

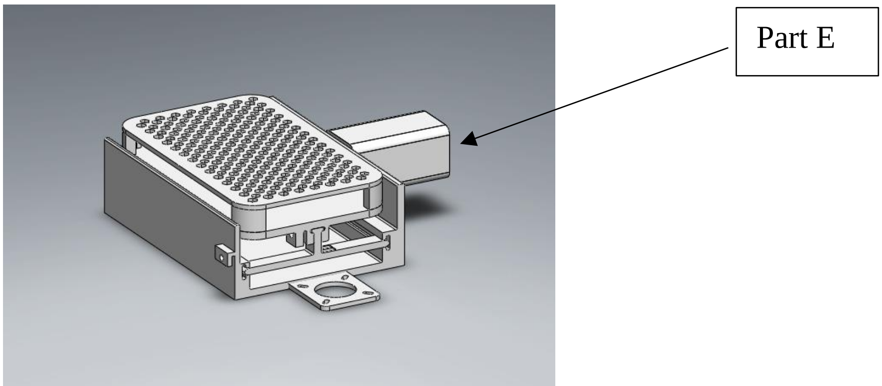

Figure 3.1-19 Added Part E in Shuttle System

3.1.3.3 Delivery box

Configuration 1:

When in the designing stages, the first design for the delivery box looked like the one shown in the figure 3.1-20. This was designed keeping in mind that the boxes will be manufactured using 3D-printer. The issue was that this will increase the cost of the system, but the idea of the team is to manage the cost so there had to be a different approach.

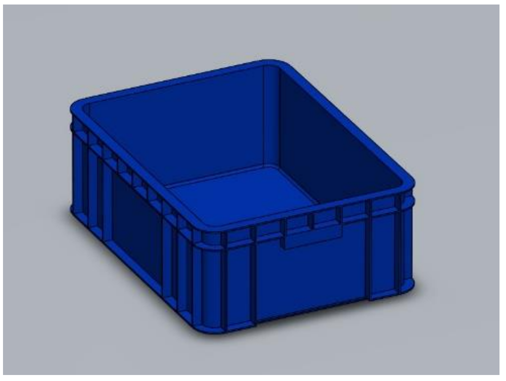

Figure 3.1-20 3D-printed delivery box

Configuration 2:

To overcome the expenses of PLA and electricity bills. The team decided to use cardboard delivery boxes, as shown in figure 3.1-21, since it will save the amount of time taken to print the boxes, it will be cheaper than using PLA and will not include electricity bills.

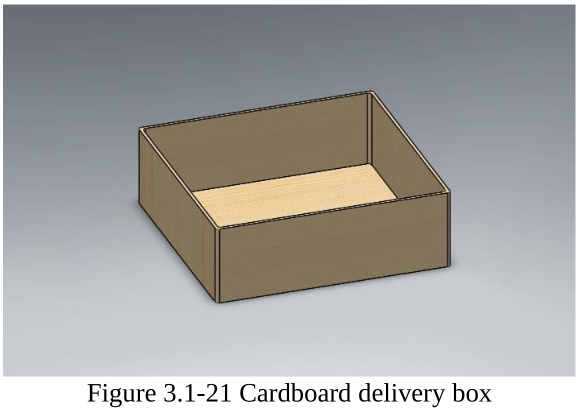

Figure 3.1-21 Cardboard delivery box

Configuration 3:

While in the testing process, the boxes in second configuration were found to be a bit bigger than the expectation. This made the delivery process harder and inaccurate. So, the new box was designed, again using cardboard, with exactly half of the size of the second configuration. The sizes could be seen in the appendix. The issue faced by the second configuration is shown in figure 3.1-22 and the new design is shown in the figure 3.1-23.

Figure 3.1-22 Issue with configuration two

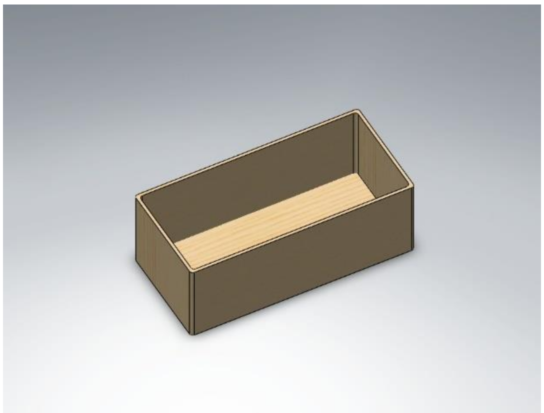

Figure 3.1-23 Box configuration three

3.1.4 Material selection

In order to choose between which materials to use, the team decided to work it out using Pugh's matrix method. It clearly showed which materials are beneficial for this project. The Pugh's matrix table 3-2 is shown below:

Table 3-2 Selection of material

Issue	Weightage (%)	Steel	Aluminum	Plastic	Titanium
Cost	35	1	0	1	-1
strength	20	1	1	-1	1
Reliability	20	1	1	0	1
Availability	25	0	1	1	-1
Total	-	3	3	1	0
Weighted total	100	55	65	40	-20

In the table above, it shows that the most beneficial materials to use for this project are steel and plastic. The maximum weightage was given to the cost as it is one of the most important factors to look after. Upon this, the team decided to go for aluminum beams and extrusions in order to create the rack and crane system, while for the materials to have some shaped design, the team took an advantage of 3D printing technology and used ABS/PLA material for such designs.

3.2 Engineering standards

The electrical and mechanical components used in the project are listed in the table 3-3 below according to their standards and are referenced in the references chapter.

Table 3-3 Key standards

SYSTEM	PART NUMBER	SUB-SYSTEM	STANDARD	REFERENCE
MECHANICAL	SH-04	GT2 belts	ISO 17396:2017	(ISO, 2017)
	SH-12	Aluminum rods	20x40-5	(T-slot)
	E-08	Stepper motors	NEMA	(Gonzalez, 2017)
	MM-01	3D - Printing	AMSS	(Stevenson, 2018)
	SH-05	Screws, Nuts, Washers	ISO 262: 1998	(ISO, Metric Screw Threads, 1998)
ELECTRICAL	E-02	Arduino	IEEE std 1855	(Vitiello, 2017)
	E-03	Raspberry pi	RoHS3 & REACH	(Adams, 2020)
	E-11	Wiring Regulations	BS 7671:2008	(BSI, 2018)
	E-13	Emergency Switch	ISO 13850 / 4.4.4	(ABB)
	E-04	RFID	ISO 15459	(ISO, RFID standards, 2003)

3.2.1 Software Standards

In order to make the software more readable for the developer and easy to debug the team followed a certain standard style in the code, which also enable each member of the team to work anywhere in the source code without needing to recognize and adopt a different programming style. Also, to be easy for other developers to contribute in case of need to help or publishing the source code. Moreover, the primary benefit of adhering to software standards is efficiency. So, the team chose the following well known coding styles to follow in the software design.

a) Style guide for python code PEP 8

The team is using PEP 8 standard to improve the readability of the Python code by choosing sensible variable names and avoiding any naming conflicts. (Python, 2001)

b) ROS developers guide

The team is following the ROS developers guide since our main program is been develop on top of ROS, which maximize or software organization and make it accessible to develop in future (Foote, 2019).

c) ROS C++ Style Guide

In order to make our C++ codes organized and easy to follow and debugging we are following the ROS C++ style Guide as our standard for developing C++ codes in our ROS packages (Hepeyiler, 2021).

3.3 Design calculations

- Maximum Payload Capacity of stepper motors:

  At 24V 600 RPM:

  Torque: 3.2 $\frac{kg}{cm}$

  “Radial 29 N (6.5 lbs.) At Flat Center”

- X-axis max payload:

  Stepper motor maximum payload = 3000g

  Nema 17 mass = 280g

- Y-axis structure mass = 694.2g

  Surface area = 171.4 mm^2

  Length = 1.5m

  Density = 0.0027 g/mm^2

  Mass = A*L*D

Max payload = 2077.8g

Z-axis max payload = 3000g

Therefore, the payload must not exceed 2 kg

3.4 Reliability Analysis

3.4.1 Failure Data/ Failure Rate of Components and Systems

Some components which are expected to fail are listed in the table 3-3 with mean time before failure over mean time to failure.

Table 3-4 Failure Data

Component	MTBF/MTTF	Failure Rate Using MTBF (FIT)	Failure Rate (FIT)	Operating condition(C)	Data Source
Nema 17	406,500 hours	2460	3440	65	(moons industries, n.d.)
GT2-2M Timing Belt	3,000 hours		-	-	(SDP/SI, nd)
Logo 12/24RCE	146,2 years	77	-	40	(Siemens, nd)
LOGO! Power supply	35,00000 hours	285	-	40	(Siemens, nd)
Pololu DRV8825	1.96E9 hours	0.51	0.5	55	(Texas Instruments, nd)
Ball Bearing 625 2RS 5x16x5	2.93E5 hours	3412	3420	30	NSWC

Probability of failure from modeling bathtub curve formula. From this a table 3-5 is generated to show the probability of failures.

$$P(t) = 1 - e^{-t/MTBF}$$

System life to retirement = 35 years = 306,600 hours

Table 3-5 Probability of Failures

Component	P(t)	Percentage	R(t)
Nema 17	0.5296	52.96	0.4704
GT2-2M Timing Belt	1	100	0
Logo 12/24RCE	0.024	2.4	0.976

LOGO! Power supply	0.084	8.4	0.916
Pololu DRV8825	0.000156	0.0156	0.9998
Ball Bearing 625 2RS 5x16x5	0.6488	64.88	0.3512

3.4.2 Reliability Block Diagram (RBD)

Reliability block diagram without any standby units is shown in the figure 3.4-22.

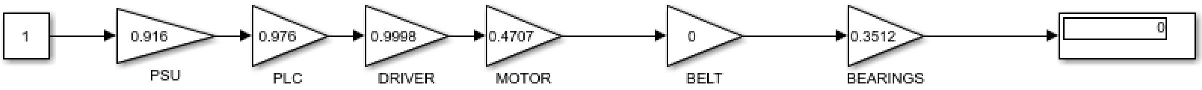

Figure 3.4-24 RBD without standby units

Number of parts (N) needed for smooth operation can be estimated using the following forluma shown in the figure 3.1-23 below.

$$\overset{*}{N} = \frac{t}{\bar{T}} + \sqrt{\frac{t}{\bar{T}} \times Z} \qquad (5.6)$$

where

t = Operation in hours

$\bar{T} = \frac{1}{\lambda}$, where λ = failures per hour

Z = 1.65 for 95 % confidence and 2.33 for 99 % confidence

Figure 3.1-25 No. of Parts needed calculation (Salih O. Duffuaa)

Assuming perfect switching and that the cold standby units are available. The table 3-6 shown the failure probabilities and number of replacements needed.

Table 3-6 Failure Probabilities and number of replacements needed

Components	No. of units needed	New R(t)
Nema 17	3	0.96
GT2-2M Timing Belt	118	0.91
Ball Bearing 625 2RS 5x16x5	3	0.91

The reliability block diagram with the standby units shows that this automated storage and Retrieval System has a reliability of 71.06% as shown in the figure 3.4-24 below.

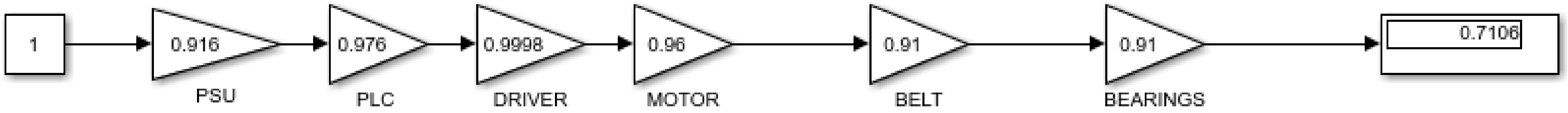

Figure 3.4-26 RBD with standby units

3.4.3 Fault Tree Analysis (FTA)/ Event Tree Analysis (ETA)

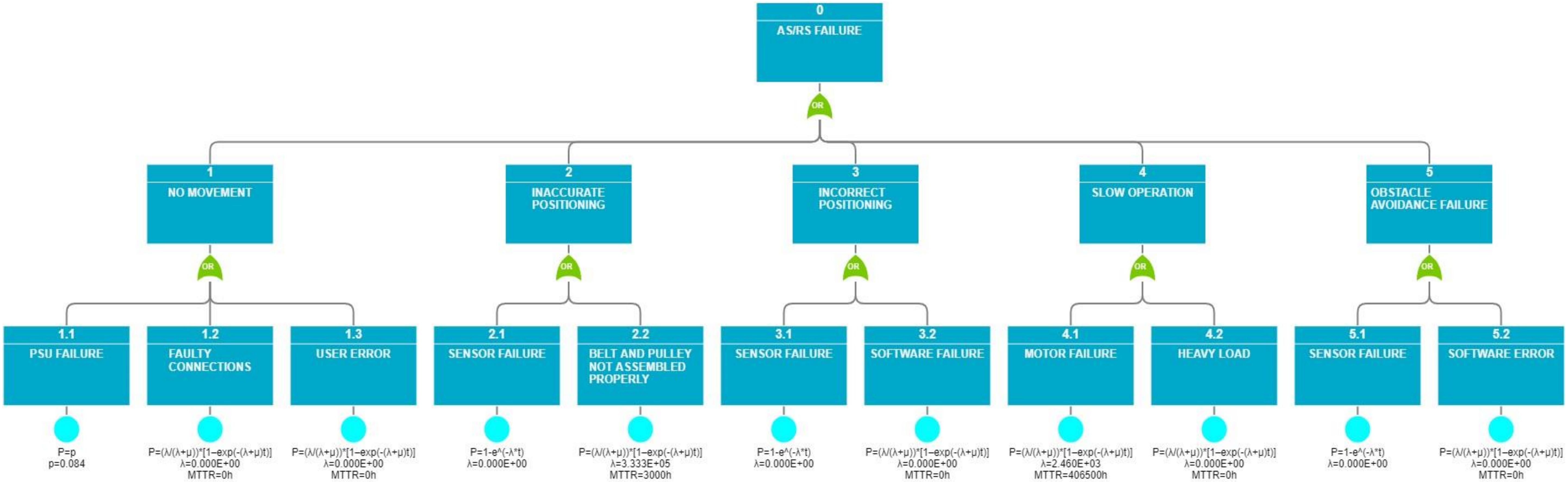

Figure 3.4-27 Fault Tree Analysis

3.5 Cost Analysis

As the research was being carried away, the bill of materials was also being prepared on the other side. As the total cost is a concern for the team, so the members had to make some meetings for choosing the components which are financially affordable, as well as, good enough to perform this project.

The team has tried to list all the equipment needed to perform this project and have researched about their value in the local and online market. This list also states whether the material is to be bought from the online market or from the local hardware shop.

The estimated cost for working on this project has been shown in the Primary Bill of Material table 3-7 which was made before the covid-19 lockdown. As it includes all the expenditures, such as, material cost, shipping charges, taxes, electric bills, etc. Although the final Bill of Material after the lockdown was over is shown in the table 3-8.

Table 3-7 Primary Bill of Materials

Bill of Material						
Product: Automated Storage and Retrieval System						
Assembly: Storage Structure						
Item #	**Part #**	**Qty**	**Name**	**Material**	**Source**	**Price ($)**
1.	161-1	27m	20x20 Aluminum Extrusion	6063-T6 Aluminum	Memocan Aluminum Ltd. Location: KKTC-Famagusta/Mormenekşe	6.7/m
2.	261-2	18	Cube Connector	ABS	In house	-
Assembly: Shuttle						
3.	161-3	9	Double Tee Nut	-	OpenBuilds Part Store 719 Whig Lane Monroeville, NJ 08343 United States of America	0.69

4.	161-4	10	Aluminum Spacers – t=6mm	-	OpenBuilds Part Store 719 Whig Lane Monroeville, NJ 08343 United States of America	2.49
5.	161-5	4	Low Profile Screws M5 – 25mm	-	OpenBuilds Part Store 719 Whig Lane Monroeville, NJ 08343 United States of America	1.39
6.	161-6	4	Eccentric Spacers – t=6mm	-	OpenBuilds Part Store 719 Whig Lane Monroeville, NJ 08343 United States of America	1.99
7.	161-7	2	Tee Nuts – M5	-	OpenBuilds Part Store 719 Whig Lane Monroeville, NJ 08343 United States of America	2.99
8.	161-8	4	Button Head Screws M3 – 8mm	-	OpenBuilds Part Store 719 Whig Lane Monroeville, NJ 08343 United States of America	0.99
9.	161-9	4	Low Profile Screws M5 – 8mm	-	OpenBuilds Part Store 719 Whig Lane Monroeville, NJ 08343 United States of America	0.99
10.	161-10	16	Low Profile Screws M5 – 6mm	-	OpenBuilds Part Store 719 Whig Lane Monroeville, NJ 08343 United States of America	0.89
11.	161-11	1	Low Profile Screws M5 – 35mm	-	OpenBuilds Part Store 719 Whig Lane Monroeville, NJ 08343 United States of America	1.59
12.	161-12	4	Button Head Screws M3 – 12mm	-	OpenBuilds Part Store 719 Whig Lane Monroeville, NJ 08343 United States of America	0.99

13.	161-13	2	GT2 – 2M Timing Pulley – 20 Tooth	-	OpenBuilds Part Store 719 Whig Lane Monroeville, NJ 08343 United States of America	5.99/p
14.	161-14	6m	GT2-2M Timing Belt	-	OpenBuilds Part Store 719 Whig Lane Monroeville, NJ 08343 United States of America	0.8/m
15.	161-15	4	Solid V Wheel Kit	-	OpenBuilds Part Store 719 Whig Lane Monroeville, NJ 08343 United States of America	5.19/p
16.	161-16	4	Delrin Mini V Wheel Kit	-	OpenBuilds Part Store 719 Whig Lane Monroeville, NJ 08343 United States of America	4.49/p
17.	216-17	1	Motor Mount Plate – NEMA 17	ABS	In house	-
18.	261-18	1	Mini V Wheel Plate	ABS	In house	-
19.	261-19	1	V-Slot Gantry Plate Universal	ABS	In house	-
20.	162-20	3	NEMA 17 Stepper Motor	-	Jiangsu Novotech Electronic Technology Co., Ltd. Location: Jiangsu, China Tel: 86-510-85389002	19/p
21.	161-21	1	Smooth Idler Pulley Kit	-	OpenBuilds Part Store 719 Whig Lane Monroeville, NJ 08343 United States of America	5.99
22.	161-22	1.5m	20x20 Aluminum Extrusion	6063-T6 Aluminum	Memocan Aluminum Ltd. Location: KKTC-Famagusta/Mormenekşe	6.7/m
23.	161-23	2m	20x80 Aluminum Extrusion	6063-T6 Aluminum	Memocan Aluminum Ltd. Location: KKTC-Famagusta/Mormenekşe	7/m
24.	261	-	Z-Axis	ABS	In house	-

Assembly: Electronics						
24.	162-24	4	Pololu DRV8825	-	Pololu Co. (702) 262-6648 920 Pilot Rd. Las Vegas, NV 89119 USA	8.95/p
25.	162-25	1	Starter kit 12/24RCE Siemens LOGO! 6ED10573B A010AA8	-	Siemens Co. Ltd. Location: Turkey Tel: 444 0 747* E-mail: callcenter.tr@siemens.com	210
26.	162-26	1	QR Code Reader	-	Banggood.com	26.9
27.	162-27	1	Arduino Mega	-	https://www.arduino.cc/	20
28.	162-28	1	Rasberry Pi 4	-	RASPBERRY PI FOUNDATION UK REGISTERED CHARITY 1129409	50
Miscellaneous and Indirect costs						
29.	-	1	3D printer	-	-	
30.	-	-	3D printing filament	ABS	-	45
31.	-	-	Assembly tools	-	-	
32.	-	-	Labor	-	-	
					TOTAL	670

m: meter

p: piece

t: thickness

161: Structure

261: Custom Structure

162: Electronics

Table 3-8 Final Bill of Material

Assembly: Storage Structure						
Item #	**Part #**	**Qty**	**Name**	**Material**	**Source**	**Price ($)**
1	ST-01	28m	20x20 L channel aluminum		Gazikent - Nicosia	27
2	ST-02	27m	Slotted aluminum bracket		Gazikent - Famagusta	9.5
3	ST-03		M6 Screws and nuts		Tekzen	4.1
4	ST-04	14	Bins	Cardboard	Info Copy Centre	18
Assembly: Shuttle						
5	SH-01	10	6mm spacers	ABS	In house	
6	SH-02	4	6mm ecentric spacers	PLA	In house	
7	SH-03	9	Double tee nut	ABS	In house	
8	SH-04	9m	GT2 Timing belt		robitistan	20
9	SH-05		Screws and nuts		Şener oğlu	45
10	SH-06	10	V wheels		robitistan	5.5
11	SH-07	1	Motor mount plate	ABS	In house	
12	SH-08	1	Mini V wheel plate	PLA	in house	
13	SH-09	1	V-slot Gantry Plate	Aluminum	Ozis	55
14	SH-10	1	Smooth idler pulley	ABS	in house	
15	SH-11	1	Z- axis assembly	PLA	In house	
16	SH-12	3m	20x40 Aluminum Extrusion	6063-T6 Aluminum	GLOBAL BAGLANTI ELEMANLARI TEKNİK HIRD VE	29
17	SH-13	2	Stand	PLA	In house	
18	SH-14	1	Paint		Local Vendor	3.5
Assembly: Electronics						

19	E-01	4	Pololu DRV8825		robistan	5.5
20	E-02	1	Arduino Mega		https://www.arduino.cc/	43
21	E-03	1	Raspberry Pi 4		RASPBERRY PI FOUNDATION	66
22	E-04	1	RFID Module		robistan	11
23	E-05	5	Limit switches		robistan	3.4
24	E-06	1	Reramps 1.4		robistan	5
25	E-07	2	IR Sensor		robistan	10
26	E-08	4	Nema 17 Stepper Motor		robistan	80
27	E-09	1	Power Supply		Özcan	26
28	E-10	1	SD-Card		Local Vendor	16.5
29	E-11	1	Wiring		Tekzen	17
30	E-12	1	Raspberry pi 4 power supply		Robistan	13.15
31	E-13	4	Buttons		Elektrokur	13.5
32	E-14	1	Junction box		Elektrokur	10.2
Miscellaneous and Indirect costs						
33	MM-01	1	3D Printer			
34	MM-02		3D printing filament	ABS, PLA		110
35	MM-03		Assembly tools			10
36	MM-04		Labor			
37	MM-05		Fuel			60
					TOTAL	**716.85**
	ST-XX		STORAGE STRUCTURE ASSEMBLY			
	SH-XX		SHUTTLE ASSEMBLY			
	E-XX		ELECTRONICS ASSEMBLLY			

MM-XX	MISCELLANEOUS AND MANUFACTURING

3.5.1 Cost Calculations of the 3D Printed Parts

1. Electricity Cost

One of the most effective factors in pricing parts created with 3D printers is electricity. While calculating the electricity cost of the 3D printer, the references of the 2020 electricity rate published by the Turkish Republic of Northern Cyprus as shown in the table 3-9, were taken. Added to it, the table 3-10 shows the power consumed by the Creality 3D printer.

Table 3-9 Electricity rates (Zamanli Tarife, 2020)

Periods	Weekdays	Weekends and Holidays
Non-working hours	23:00-09:00; 0.6508 TL/kWs	02:00-09:00; 0.6308 TL/kWs
Normal hours	18:00-23:00; 0.9875 TL/kWs	09:00-14:00 and 18:00-02:00; 0.9873 TL/kWs
Rush hours	09:00-18:00; 1.2908 TL/kWs	14:00-18:00; 1.2708 TL/kWs

- We assumed that we will print our parts only weekdays.
- The US dollar to Turkish Lira conversion rate these days is about 6.77TL per dollar.
- 3D Printer power is 270 Watt and Heater bed power is 30 Watt (CR-10 3D-printer power, n.d.)
- Total Power = 300 W = 0.3 KW

Table 3-10 About Creality 3D printer (CR-10 3D-printer power, n.d.)

Model Number	CR-10S	**Machine Power**	270W
Built size	300*3*400mm	**Rated Voltage**	220V 50Hz 110V 60Hz
Machine size	600*590*610mm	**Filament**	PLA
Molding technology	FDM	**Filament diameter**	1.75mm
Net weight	9KG	**Manufacture date**	2018

- **Average Electricity Rate** = [(10x0.6508) + (5x0.9873) + (7x1.2908)]/24 = 0.9356 TL/kWh

  = 0.1382 $/kWh

- **Electricity Cost** = Print Time x Quantity x Total Power x Average Electricity Rate (Mucha, n.d.)

Table 3-11 Electricity cost table

Part Name	Quantity	Print Time (Hour)	Total Power (kW)	Average Electricity Rate ($/kWh)	Electricity Cost ($)
Vasi2	1	23.85	0.3	0.1382	0.989
Fork	1	8.38	0.3	0.1382	0.347
Motor Mount Plate Nema17	3	1.27	0.3	0.1382	0.159
Mini V Wheel Plate	1	1.27	0.3	0.1382	0.053
V-Slot Gantry Plate	1	1.75	0.3	0.1382	0.073
Vasi3	1	0.92	0.3	0.1382	0.038
Cube Corner Connector	18	0.58	0.3	0.1382	0.432
				Total Electricity Cost = $2.1	

The table 3-11 above clearly shows the estimate electricity cost for printing out those materials. To be noticed, these estimates are as per today's power rates.

2. **Filament Cost**

Filament is the general name of the material used in 3D printers. ABS (Acrylonitrile Butadiene Styrene) filament was used in this project. Most of the costs of the printed parts are filament costs. Table 3-12 shows the estimate cost of filament to be used in printing out those materials.

- 1Kg Rohs ABS 1.75mm Filament is $14.77, this mean 1 gram of the ABS filament is around $0.015.
- ABS cost per gram is $0.015.
- Filament Cost = The weight of the printed part x ABS cost per gram

Table 3-12 Total filament cost

Part Name	Weight of the Printed Part (Gram)	ABS Cost ($/g)	Filament Cost ($)
Vasi2	228	0.015	3.42
Fork	81	0.015	1.215
Motor Mount Plate Nema17	24	0.015	0.36
Mini V Wheel Plate	12	0.015	0.18
V-Slot Gantry Plate	14	0.015	0.21
Vasi3	8	0.015	0.12
Cube Corner Connector	60	0.015	1.35
		Total Filament Cost = 6.855 $	

3. Total Cost of the 3D Printed Parts

Finally, the total cost of the 3D printed parts is equal to sum of the electricity cost and total filament cost but as we know 3D printers or users can make same mistakes and these mistakes can affect the part because of this part may need to be print again.

- Assumption of the error rate is 20% (3D Printing Failure Rate) (Nuchitprasitchai, 2017)
- Total Cost = (Total Electricity Cost + Total Filament Cost) x (1.2)

= (**2.1 + 6.855) x 1.2**

= 10.746 $

CHAPTER 4 - MANUFACTURING and ASSEMBLING

4.1 Manufacturing process selection

In this section, table 4-1 and 4-2 will show some major and basic manufacturing plans and assembly plans which will be described in more details once the team get their hands on the materials and components.

Table 4-1 Manufacturing Plan

No.	Part Name	Part Name	Vendor	Machine	Process
1.	ST	Storage Rack	Local market	N/A	Main frame parts will be bought off the shelf in custom sizes and will be assembled using screws and nuts.
3.	SH-11	Pallet system	In Home Local vendor	3D printer	Most of the pallet system is going to be manufactured using 3D printer and some other materials which will be bought off the shelf.
4.	E-1-1-2	Electronics	Online and local market	N/A	Electronic equipment such as raspberry pi, Arduino, ramps 1.4 and RFID etc. will be bought off the shelf.
5.	H-1-1-1	Mechanical	Online and local market	N/A	Parts such as motors and belts will directly be ordered off the shelf. Some materials will be manufactured using 3D-printer and from aluminum factory

Table 4-2 Assembling Plan

No.	Part Name	Part name	Assembly
1.	ST	Storage rack	The aluminum rods will be fixed together in a shape of box, which will consists of multiple boxes within it, this will be done by using screws and nuts.
2.	SH-11	Pallet system	Combination of motors, gears and belts and a shuttle will be assembled to bring up the pallet system.
3.	SH-00	Shuttle	Shuttle will be assembled with a motor and belts.
4.	E-1-1-2	Electrical components	Connecting arduino with ramps 1.4 and adding drivers and adding other components to perform tasks with motors.

4.2 Detailed manufacturing process

The manufacturing process for this automated storage and retrieval system will mainly consist of buying and shipping of materials, creating and printing of the 3D designs and models and then finally assembling these to become a working ASRS system. These processes have been mentioned in details below.

In the manufacturing process, the team has used a CREALITY 10S 3D printer, as shown in the figure 4.1-1 below, which was an advantage for the accuracy of the printed objects. As it comes with a 0.4mm nozzle which results in high precision printing. CR-10S has the ability to resume prints even after a power outage or lapse occurs (CREALITY, n.d.). All this came in favor to the team as there were less concerns about the size problems or any power outage.

Figure 4.1-1 CREALITY 10S 3D printer

1. Parts to be 3D Printed:
   a) SH-01
   b) SH-02
   c) SH-03

d) SH-07

e) SH-08

f) SH-10

g) SH-11

h) SH-13

ABS plastic was chosen as a printing material over PLA. ABS (Acrylonitrile Butadiene Styrene) plastic is a thermoplastic polymer often used in the injection molding process. It is one of the most common plastics used in OEM part production and 3D print manufacturing. ABS is relatively safe to handle as it cools down and hardens, making it one of the easiest plastics to handle, machine, paint, sand, glue, or otherwise manipulate (ABS Plastic, n.d.).

The storage rack of this system will be designed using the aluminum T-Slot 20x40 rods and aluminum Q8mm tubes which will be bought off the shelf from a local vendor which means that it will not consume a lot of time for the production of storage rack.

4.2.1 Manufacturing and assembling

As listed in the table 4.1, it can be seen that most of the manufacturing will be done using a 3D printer. ABS will be used to print some of the mechanical body and equipment. The designs will be printed with the help of some software like Cura (for 3D-printer), SolidWorks and Fusion360 (for the designs and .stl files). Meanwhile the aluminum rods will be bought from the local market and the other needed tools like saw, soldering machine, screws and nuts etc. will also be taken off the shelf through local vendors or can be used in mechanical workshop in EMU campus. Once the 3D designs are printed and all the other materials are bought, then the team will finally be ready for the assembling of this project.

Since most of the design is 3D printed and the T-Slot aluminum frame, thus the assembly will be simple. Since the nuts and bolts will not be 3D printed, so they will be according to some standard. Of course, while assembling, the motors and electrical wires etc., will come together which can make the assembly process consume more time, since, it will require to arrange the equipment in a specific order and to start the assembly from base. Assembling items separately and then bringing them together to end the automated storage and retrieval system will be the goal. For instance, the team will be divided into groups for the assembly of the storage rack to be done separately while on the other hand the assembly of the 3 degree of freedom pallet will be taking place etc. Then all of this with PLC will be attached together on the base and the coding period will begin. Using a kit of multi toolbox to assemble those components into a model by mechanical means of drill machine and screw drivers, cutters and pliers.

1. Storage Structure Assembly:
   a) Part no. ST-01will be cut various lengths using a saw according to engineering drawing no. ST-01 in appendix F
   b) All cut parts will be assembled according to engineering drawing no. ST in appendix F
2. Shuttle Assembly:
   a) X-axis will be assembled using documentation provided by OpenBuilds (V-Slot NEMA 17 linear actuator, n.d.)
   b) Z-axis will be assembled using documentation provided by OpenBuilds (V-Slot NEMA 17 linear actuator, n.d.)
   c) Axis X, Y and Z will be assembled according to engineering drawing no. 261-ZX in appendix F.

3. Electronics:
   a) All electronics and related items will be assembled according to the circuit diagram from various sources and data sheets in appendix G.

4.3 Detailed assembling process

In this section, the team will describe the assembling of all the components and bringing them together to form a working automated storage and retrieval system. Firstly, the electrical schematics will be discussed, which will be followed by the mechanical model and in the end, some details about the program will be given.

4.3.1 Electrical assembly

Two team members took the responsibility for working in the electrical section. Firstly, the power supply was arranged after performing some mathematical problems, the maximum voltage and current was calculated. So 12V and 20A power supply was bought from the local vendor and then was wired to work with this project as shown in figure 4.3-1. A little detail to be seen is that as shown in the figure 4.3-2, there can be seen a small yellow screw which is given to adjust voltage and the green light represents that either the power supply is ON/OFF.

Figure 4.3-1 Power supply

Figure 4.3-2 Voltage adjusting screw

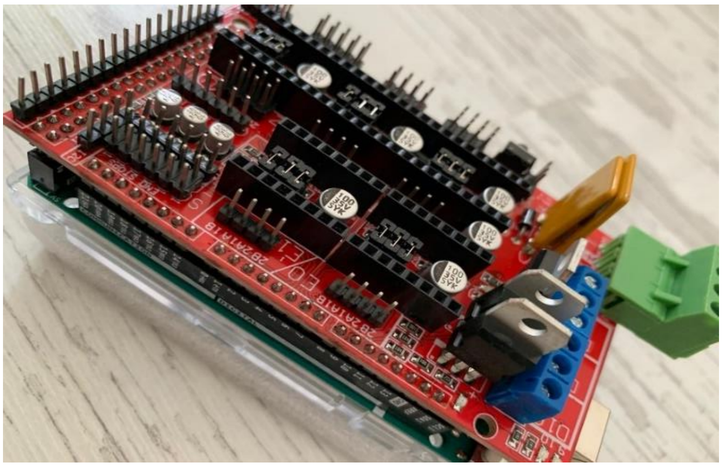

Figure 4.3-3 Arduino and ramps 1.4

Secondly, the Arduino board was connected with the ramps 1.4 for running the drivers to control the motors as shown in the figure 4.3-3 above. Once the Arduino and ramps 1.4 were connected, the next step was to figure out how to connect the drivers on the ramp 1.4. There were plenty of things that were learnt, how to connect it in the right direction, the mini screwhead type looking potentiometer on the drivers is to control voltage flow. This A4988 driver allows you to set a target current anywhere between a small mA up to a 2A and this is achieved by adjusting a small screw looking Vref (reference voltage) when turning the pot on a clockwise direction the Vref voltage will increase and decrease when rotating it counterclockwise (A4988 motor driver). This is shown in the figure 4.3-4 below.

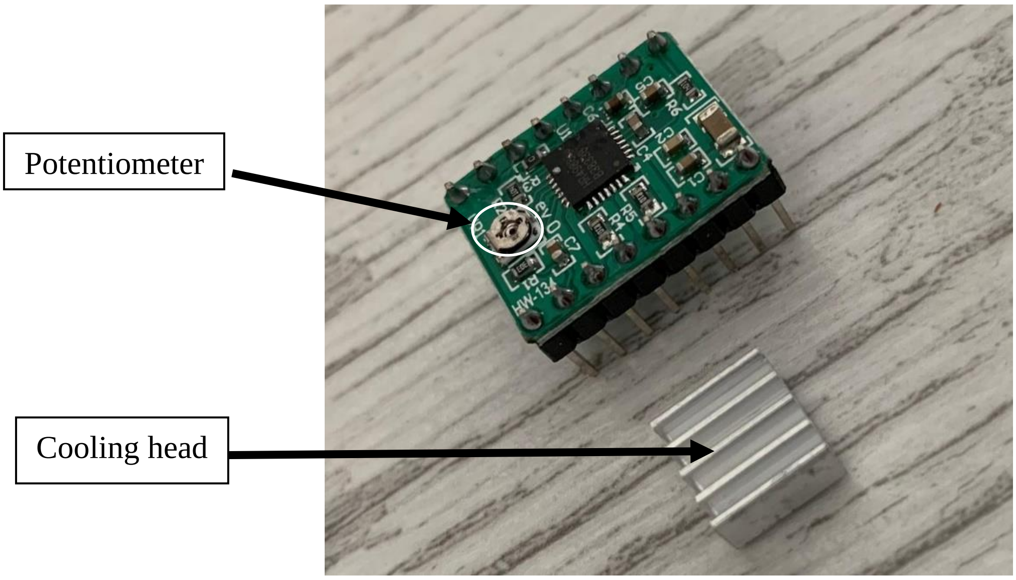

Figure 4.3-4 Stepper driver

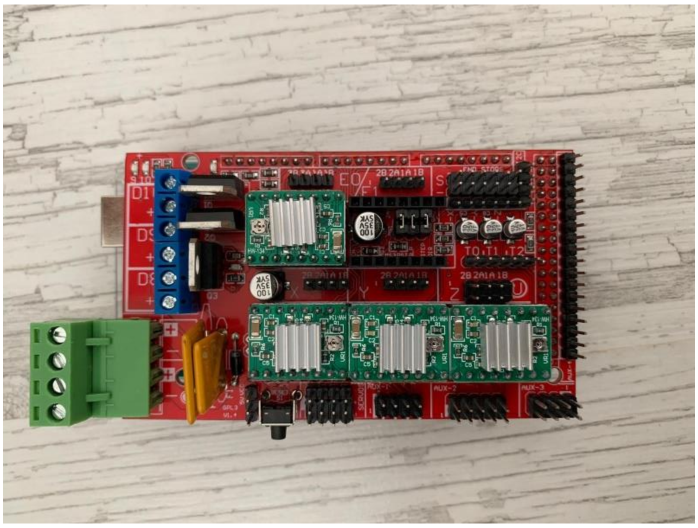

Figure 4.3-5 Arduino, ramps 1.4 and drivers connected

Once the drivers were ready as shown in the figure 4.3-5 above, it was time to connect them on the ramps 1.4 with power supply and motors. It was time to search for the circuit schematics and understand the connections and connect everything together. The schematic used for this system is shown in the figure 4.3-6 below.

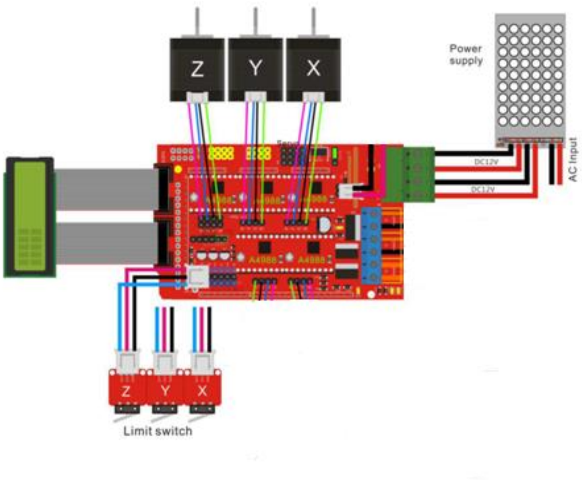

Figure 4.3-6 Electrical schematic

In the figure 4.3-6 above, it is clearly shown how the motors with axial direction of X, Y and Z are connected to the drivers on the ramp 1.4. It also shows the connections with power supply and limit switches. However, connecting the limit switches was the tricky part, as the switches showed symbols of “positive”, “negative” and “ground” while on the ramp 1.4 board, the symbols marked were “positive” “ground” and “S”. After some research, the team found “S” to be “Signal”, which had to be connected with the VCC of the limit switches. Three limit switches are used for all three motors. Finally, the whole system was ready and connected and is shown in the figure 4.3-7 below.

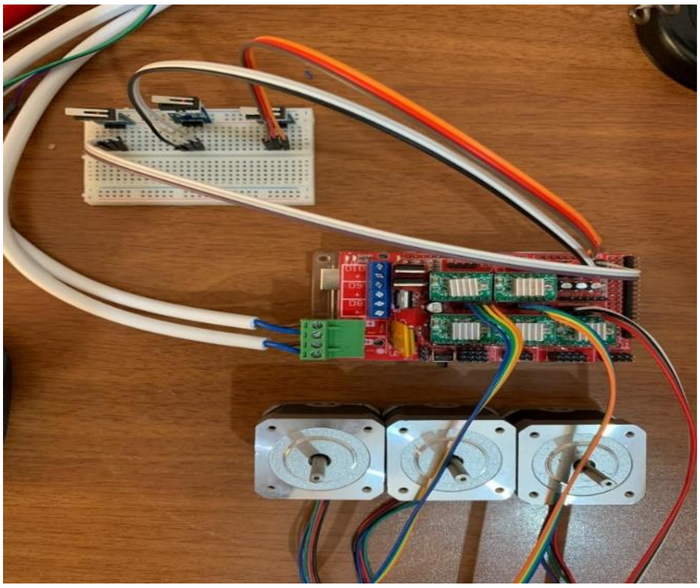

Figure 4.3-7 All system connected

The team has used these motors as bipolar steppers. Now bipolar steppers have a single coil per phase and require more complicated control circuitry. The A4988 driver has the ability to control a bipolar stepper motor. These motors usually have four cables, two for each coil. But as shown that for the movement on Y axis, after some brief testing, for more power the group decided to use a bit bigger motor nema-17, which can be used as both unipolar and bipolar. Hence is comes with six cables instead of four. Now to connect them was tricky as the member had to identify each cable (Stepper Motor). The connection has to be made as shown in the table 4-3.

Table 4-3 Connection configuration for stepper motors (Stepper Motor).

Stepper leads	**Outputs**	**Cable**
A	1A	RED

C	1B	BLUE
B	2A	GREEN
D	2B	BLACK

To connect nema-17 with A4988 drivers as a bipolar motor, the connections shown in the table 4-3 will be used but by leaving the cables A' and B' disconnected. These leads are center taps to the two coils and are not used for bipolar operation (Stepper Motor).

Note that, if the connections are swapped in which way the wires are connected for any coil, the stepper motor will turn in the opposite direction, and if the wires are paired with different coils, the motor should be noticeably unpredictable when it is to be stepped, if it even moves at all (Stepper Motor).

Once these were ready and connected, the software team can start with testing and run the program on it so that the three motors can work autonomously.

4.3.2 Mechanical assembly

4.3.2.1 Crane System

Once everything was being ready in the electrical department, the work has also been commenced in the mechanical section. The first step was to assemble the x axis. This was done by assembling the base. The key components to assemble the base are shown in the table 4-4 below.

Table 4-4 Base components

Part Number	Component	Quantity
SH-09	V-Slot Gantry Plate	1
SH-01	6mm Spacers	2
SH-02	6mm eccentric spacer	2
SH-06	V-Wheels	4

SH-05	M5 Nuts	6
SH-05	M5-35mm screws	4
SH-07	Nema-17 Motor mount plate	1
E-08	Nema 17 motor	1
SH-05	M5 precision shim	4
SH-05	M3-10mm screws	4
SH-05	M5-15mm screws	2

The M5-35mm screws were attached on every corner of the V-Slot gantry plate and then the 6mm spacers were added to the small hole to the fix wheel side and the 6mm eccentric spacers were added to the larger holes to cause preload and rotate since the eccentric essentially brings that wheel up/down to loosen/tighten to the track. Then the M5 washers were added to every screw followed by the wheels and the M5 nuts to tighten. Then the Nema 17 motor mount plate was attached to the V-slot gantry plate by M5-15mm screws and M5 nuts on the third line down the fixed screws. After that, from the top of the motor mount plate, the Nema 17 motor was attached by using M3-10mm screws. This assembly has been shown in the figure 4.3-8 below.

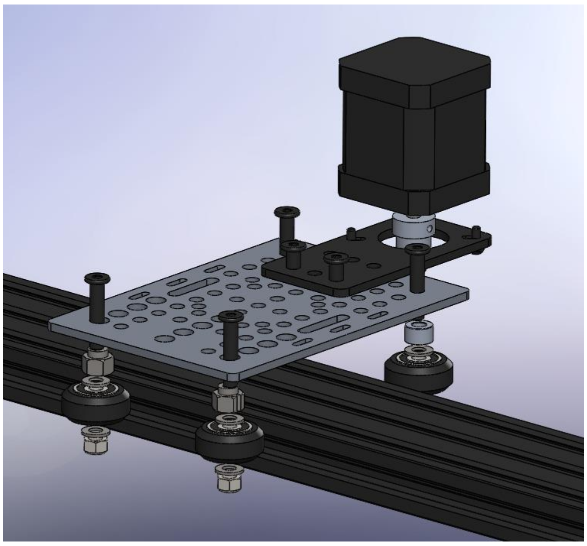

Figure 4.3-8 Gantry plate assembly drawing

Once the gantry plate was all assembled, two 20x40 aluminum rails were put together and then the V-slot gantry plate was slid in to the aluminum rails and to hold the rails tightly, the team used two zip ties on both ends of the rails. The GT2 belt was ran in the rails through the top track from one end to another. To attach the belt to the motor pulley, a team member squeezed the belt to create a tent type figure so the belt could pop up and be pulled and attach to the motor. Then the belt was pulled from each side and tightened by using T-nuts.

Once the X axis was assembled, it was the Y axis to be assembled next. The components required to assemble the Y-axis plate are listed on the table 4-5 below.

Table 4-5 Lift components

Part Number	Components	Quantity
SH-06	V-Wheels	4
SH-02	6mm Eccentric Spacers	2
SH-01	6mm Spacers	2
SH-08	Mini-V Wheel Plate	1
SH-05	M5-25mm screws	4
SH-05	M5 nuts	18
SH-05	M5 precision shim	5
SH-10	Idler Pulley	1
SH-05	M5-35mm screw	1
SH-0	End mount	2
E-08	Nema 17 motor	1
SH-05	M3-10mm screws	4
SH-05	M5-10mm screw	12

The M5-25mm screws were attached on each corner of the Mini-V wheel plate and the same steps were followed as the assembly of gantry plate above. The 6mm spacers were added to the small hole to the fix wheel side and the 6mm eccentric spacers were added to the larger holes to cause preload and rotate. Then the M5 washers were added to every screw followed by the wheels and the M5 nuts to tighten. Once the mini-V wheel plate was assembled, then it was slid into the 20x40 aluminum rails.

To assemble the aluminum rail with the system, the end mount is used on the both sides of the rail. Firstly, the end mount has to be assembled by attaching the M5-35mm screw in center hole followed by a nut (acting as a spacer), idler pulley and a precision shim in the middle of the end mount and then tightened by a nut from the other side. Now for the other end of the rail, the Nema 17 motor is entered through the center hole of the end mount and is attached with the pulley and the motor is attached to the end mount by using the M3-10mm screws.

Once the end mounts are ready, the aluminum rails are attached to them by running three nuts inside the rail on each side and then screwing the three M5-10mm screws from the end mount.

To attach the end mount to the motor base, means connecting X and Y axes. The two M5-10mm screws were used with two M5 nuts. The screws were inserted from the motor side from inside of the end mount to the gantry plate and was tightened to the base by using nuts.

Now in order to assemble the Z-axis shuttle, Parts A, B, and D are secured together with glue then are slid into part C. Then a timing belt is connected to part a, stepper motor and part c through a pulley. Table 4-6 marks the important components to assemble the shuttle while the figure 4.3-9 shows the assembly procedure.

Table 4-6 Shuttle components

Part Number	Components	Quantity
SH-05	M5-15mm screws	2
SH-05	M5 nuts	2
E-08	Nema 17 Motor	1
SH-04	GT2 belt	1
SH-05	M3-10mm screws	4

SH-03	T-nuts	4

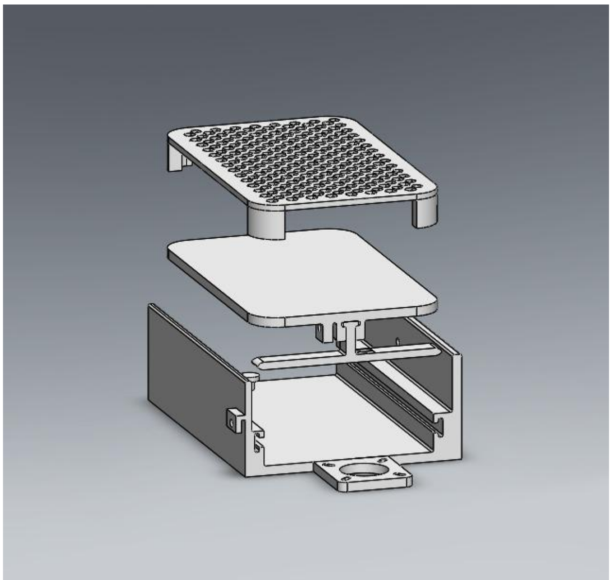

Figure 4.3-9 Shuttle assembly procedure

4.3.2.2 Storage Racking System

In order to build the rack, the L-20x20 aluminum beams were used. Firstly, they had to be arranged in four different sizes. In order to do this, the team used table saw machine available in EMU Technical Affair Workshop. The sizes were measured on the cutting table as it had the built-in metric scale. Since the team members were not allowed to use the machine by themselves, so the coordinator of the Technical Affairs ordered a worker to help with the matter. The beams were cut down in the sizes shown below in the table 4-7.

Table 4-7 L-20x20 Aluminum beams

Part Number	**Length (m)**	**Quantity**
ST-01	1	2
ST-01	1.5	17
ST-01	0.2	77
ST-01	0.26	2

Now it was the time to drill the beams so they could be attached together to form up a rack. The EMU Mechanical Workshop facility was used in order to do this job. For the 1m and 0.26m beam, they were marked and drilled hand to hand due to low quantity, but when it comes to the 1.5m and 0.2m beams, the team member made a reference point on a single beam and then it was considered as the reference beam.

For the 1m beam: On each end of the base of the L cross-section, 10mm from the length and 10mm from the width was the drilling point. Then for the height of the L cross-section, 20mm from the length and 10mm from the width was the drilling point.

For the 0.26m beam: On each end of the base of the L-cross-section, 80mm from the length and 10mm from the width was the drilling point. then for the height of the L-cross-section, 10mm from the length and 10mm from the height was the drilling point.

For the 1.5m beam: On each end of the base of the L-cross-section, 10mm from the length and 8.5mm from the width was the drilling point. Then for the height of the L-cross-section, 10mm from the length and 8.5mm from the width were the drilling points. Now to add the shelves, these drills were followed by 8 drills on the height part of the L-cross-section 150mm apart from one end, which was then considered as top point.

For the 0.2m beam: On each end of the base of the L-cross-section, 10mm from the length and 8.5mm from the width was the drilling point. Now to add home point, there was one more reference to be made in this beam. The reference point of this was also measured on the base of the L-cross-section, 100mm from the length and 8.5mm from the width were considered as reference.

So, the reference points were marked these ways. After marking these reference points, they were made permanent by using hammer and punch. Then these points were ready to be drilled.

Once the references were all settled, the team used the industrial drilling machine as shown in the figure 4.3-10 below. The drill bit used to drill these holes were all 6mm at a speed of 720 as was recommended by the technician of the workshop. after the drilling, a team member chamfered the holes to remove the metal chips.

Figure 4.3-10 Industrial drilling machine

After drilling 1m and 0.26m beam hand to hand, it was the time to drill the 0.2m and 1.5m beam. First the reference beams were drilled, then a team member made a “U” shape by putting two beams on top of each other by adjusting the edges with reference beam being on the top. Since the thickness of the aluminum beam is 1.5mm. This is why it was decided to adjust the mark on the width of the reference was set as 8.5mm, in order to create 10mm distance on the beam to be used. Additionally, for the 0.2m beam, seventy-two of them were drilled only on each end and just the four of them were drilled in center as well to be used for the home. The components to assemble storage rack are listed in the table 4-8.

Table 4-8 Storage rack components

Part Number	Components	Quantity
ST-03	M6-10mm	46
ST-03	M6-25mm	4
ST-03	M6-35mm	50
ST-03	M6-30mm	10
ST-03	M6 nuts	110
ST-03	M6 precision shims	14
L-20x20 Aluminum Beams		
ST-01	1m	2
ST-01	1.5m	16
ST-01	0.2m	66

To assemble the racking system, the assembly started from top (head). Each 1m beam was attached the top of five 1.5m beam by using M6-10mm screw with precision shim and nuts. For each front and back side of the rack, six 1.5m beams were attached to the head of the racking system 0.24m apart. The three on the middle of each side and attach another 1.5m beam to each one in order to create a square cross-section shape by using M6-30mm with precision shim and nuts. Then the 0.2m beams were attached to the 1.5m beams on the head by using M6-35mm with precision shims and nuts from top to bottom for all columns to create the shelves. Although for the side ones, the M6-10mm screws were used with nuts.

4.3.2.3 Home assembly

To assemble the home, the components and quantity of the material is shown in the table 4-9 below.

Table 4-9 Components for home

Part Number	Components	Quantity
ST-03	M6-25mm	4
ST-03	M6-30mm	8
ST-03	M6-10mm	4

ST-03	M6 nuts	16
L-20x20 Aluminum Beams		
ST-01	0.26m	2
ST-01	0.2m	10

Four square cross-sections were made using eight 0.2m beams using M6-30mm screws and nuts. Each two of the cross-section beams were attached from top to a 0.2m beam to make a stand by using M6-10mm screws and nuts. Two 0.26m beam was attached on the bottom of the stand using M6-30mm screws and nuts. Six L-20x20 aluminum beams, 0.26m, (three on each side) from first configuration of racking system were used on the center (0.1m from top) of the home to strengthen the structure by using M6-25mm screws with nuts.

4.3.2.4 Base assembly with the structure

Eighteen L – 20x20 aluminum beams, 0.2m, from the first configuration were used to attach the storage rack to the wooden chipboard base using M6-10mm screws. First the first config. Aluminum beams were attached to the 1.5m beams using four M6-25mm for the corner beams and for the middle ones by using M6-30mm screws with nuts. After that, to attach the home with the ground, the two 0.26 beams from the bottom of home structure are used itself to the wooden chipboard by using M6-10mm screws. The component list is shown in the table 4-10 below.

Table 4-10 Components for the base

Part Number	Components	Quantity
ST-03	M6-25mm	4
ST-03	M6-10mm	16
-	Wooden Chipboard	2
SH-05	3d printed lock	1
SH-05	M5-10mm	4

In this design, the home structure is flexible, in the sense that it is portable. It can be moved from right side to the left or can also be settled on top. This can be achieved by unscrewing the lock and screwing it on the other side. The screws used for this portability system is M5-10mm screws.

4.4 Software

The word Machine-to-Machine (M2M) communication can be expressed as it has a strong software system behind the actuator and the sensors in the robot. For developing the top software layer that is responsible about any part of the software system, Robot Operating System (ROS) made by Garage.W was the best option available, because it is an open-source software as well as it is the strongest robotics platform. ROS has a great and wild community around the world which will allow the team to emerge in the community and find support for problems that could arise.

ROS has a set of software libraries and tools to assist in building robot applications. Which make it way easier to build complex software systems. Since it an open-source software, the team can use other packages and codes and directly integrate it with this project and as long as the BDS license terms are being following. Finding the appropriate packages/libraries that can be used for an AS/RS system to reduce the time required to develop such system by using other work.

In short, ROS is the combination of Plumbing (or communication), Tools, Capabilities and Ecosystem. These capabilities are demonstrated in the following figure 4.4-11

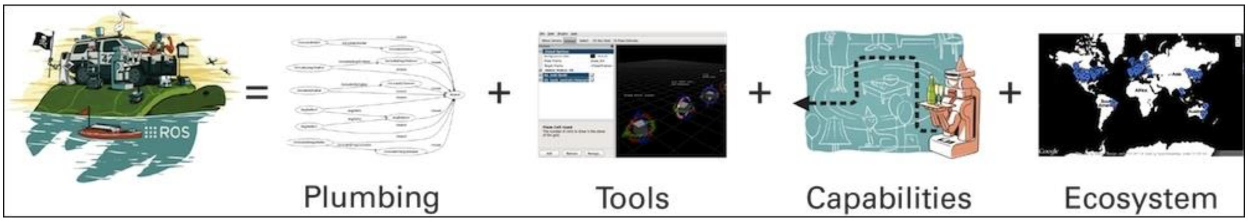

Figure 4.4-11 The ROS equation (Joseph, 2017)

ROS is providing the Publisher/Subscriber features which make each code written either in C++ or python to communicate through "Topics" which is the communication channel with a pre-defined message architecture. The team uses this feature to make machine-to-machine communication possible, by making the master device to process the operation and publish the message it needs. This is explained in the figure 4.4-12.

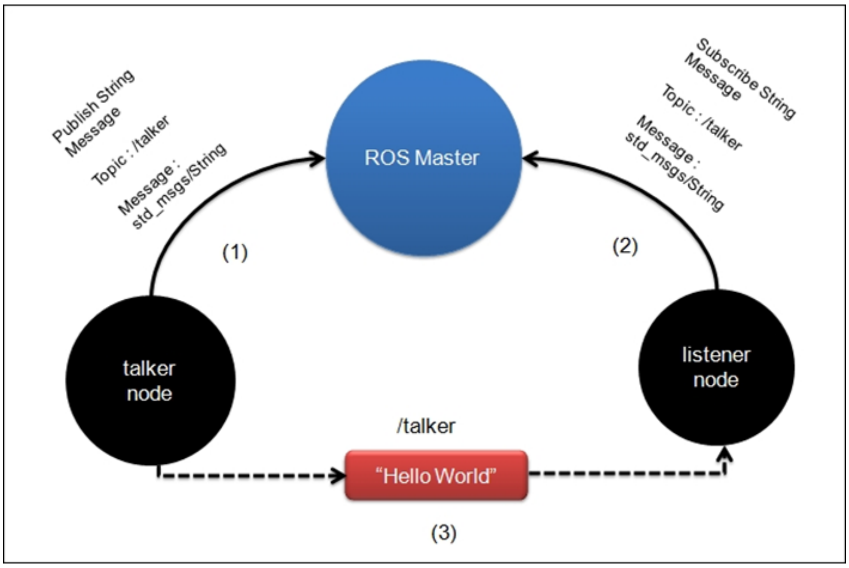

Figure 4.4-12 Communication between ROS nodes using topics (Joseph, 2017)

Robot controls is one of the essential elements in any automated robotic software system. This robot has three degrees of freedom as shown in the figure 4.4-13, so writing a controller for each degree of freedom and making sure all of them are working in harmony would be a tall order for this situation and with the current knowledge, the team decided to use the AccelStepper library to handle motion control for this project. AccelStepper allows to control a variety of stepper motors at the moment. Providing an object-oriented interface stepper motors and motor drivers.

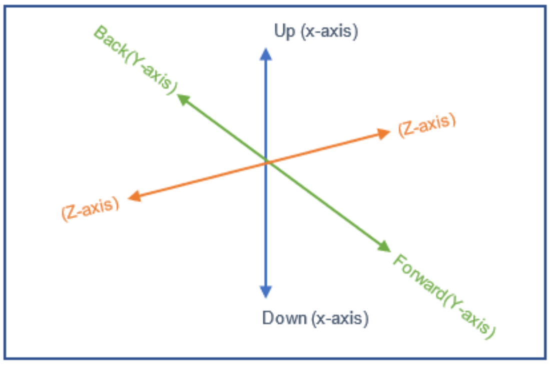

Figure 4.4-13 Three degree of freedom

What makes AccelStepper useful for this project is that it significantly improves the standard Arduino Stepper library in several ways:

- “Supports acceleration and deceleration.
- Supports multiple simultaneous steppers, with independent concurrent stepping on each stepper.
- Most API functions never delay or block (unless otherwise stated).
- Supports 2, 3 and 4 wire steppers, plus 3 and 4 wire half steppers.
- Very slow speeds are supported.
- Extensive API (Application programming interface).
- Subclass support.” (McCauley, airspayce)

4.4.1.1 Detection system

In order to achieve the M2M system, RFID software programmed was used to help a network device interpret the data and make decisions, which make M2M application to translate the data and can trigger preprogrammed automated actions.

Hours after searching for a library to integrate the RC-522 RFID readers with the Raspberry Pi, MFRC522 library was found. MFRC522 is a python library to read/write RFID tags via the budget MFRC522 RFID module. (Up, 2019)

MFRC522 library helps to define and read the RFID cards and assign their own position in this AS/RS system, which also allows to send a message to the robot by publishing through ROS.

CHAPTER 5 - PRODUCT TESTING

5.1 Verification of the objectives of the project

1. **Design for cost:**

   a) All costs, direct, indirect and variable will be accurately logged and monitored.

   b) Unnecessary shipping costs will be avoided by ordering early on or trying to find local suppliers.

2. **Design for manufacturability:**

Number of parts that were originally chosen to be bought in the design process will be compared to the actual parts that were purchased after the first design cycle.

For this design process, the team will follow some general principles in DFMA. These guidelines enable us to reduce design time, manufacturing cost and effort and the ability to replace or modify any component by 3D Printer. Table 5-1 shows the major DFMA guidelines to be followed in this project.

Table 5-1 Components Failure Rate

Guideline	Implementation and advantages
Use standard commercially available components	The team will use commercially available motors, sensors, pallet, and electrical components to reduce design effort and make sure that these components are quality controlled.
Use common parts across the proposed configuration	The following parts will be group manufactured / purchased: • 3D printed wheel plate • Frame • Motor sliders • Aluminum Extrusion
Design for ease of part fabrication	All the parts will be made to either be manufactured or 3D printed. This strategy enables us to manufacture the number of parts in less than a week.

Design the product to be foolproof during assembly	This AS/RS can be easily assembled by following the assembly sequence explained in chapter 4 table 4-2.
Minimize use of flexible components	There are no flexible components used which facilitates handling and assembling the AS/RS.
Use modular design	This design can be adjusted according to the desire need, it consists of 3 stepper motors which allows the system to move in three direction (X, Y and Z)

3. **Design for reliability:**

Design for reliability is also one of the major factors in this project, as the more reliable the design is, there would be less chances of failure during the presentation of this project, or even if the project is being used by the university in the future to show the young freshmen of mechatronics engineering to inspire them and motivate them for performing better.by the university in the future.

5.2 Reliability Testing

Reliability Testing is an important software testing technique that is performed by the team to ensure that the software is performing and functioning consistently in each environmental condition as well as in a specified period. Table 5-2 shows some departments for testing.

Table 5-2 Stresses to be applied (Kentved, 2011)

Stress	Wearout Failure Mechanisms	Overstress Failure Mechanisms
Temperature	Diffusion, Evaporation Thermal ageing (Polymers)	Melting, Freezing, Boiling, Explosion, Tg transition
Humidity	Sorption, Corrosion	Condensation
Vibration	High Cycle Fatigue (HCF)	Mechanical overload, Microphony, Rattling
Thermal Cycling	Low Cycle Fatigue (LCF)	Same as for temperature overload
Voltage	Time dependent dielectrical breakdown	Electrical overstress, electrostatic discharge

Current	Electromigration	electrical overstress
Others	Creep, Wear, Ultra Low Cycle fatigue	Impact
Combined	Fretting corrosion Migration, Corrosion, TDDB, Electromigration	Same as all the failure mechanisms above

Some components which may fail easily are listed in the table 5-3 and what can accelerate their failures so the precautions may be taken to avoid such failures.

Table 5-3 Potential failure modes to be tested

Failure Mode	**Failure mechanism**	**Accelerating Factors**
Sensor Failure	Various	Humidity, Voltage, Temperature
Power failure	Various	Humidity, Voltage, Temperature, Electric Field
Belt and pulley	Fatigue	Thermal cycling & vibration
Software	-	-

Calibrated Accelerated Life Testing (CALT) (GMW-8758) will be used to test the system.

The system reliability performance is poor at only 71% reliability even considering the fact that the values used were conservative. Any system that could affect human life should be as close as possible to 100%.

1. Using industry level components.
2. Performing in house CALT for components and assemblies
3. Using both field data and reliability prediction standards.
4. De rating
5. Adding more redundancy on a component level.

5.3 Verification of the applied engineering standards

To verify the engineering standards for this project, the mentioned sections of the following standards will be applied. These are shown in the table5-4 below.

Table 5-4 Applied engineering standards

Application Area	Standards	Remark
AS/RS	ASME B30.13-2011 Storage/Retrieval	Partially followed due to the fact the standard specifications that can only be applied to full size AS/RS application.
Software	ANSI/ISA - S5.1-1984 (R1992)	Used for electrical component symbols in circuits
	ISO 128	
Reliability	IEEE STD 493-1997	Reliability of the power system
Material Handling	NIST Material Handling 1998	Partially followed due to the fact that the paper is technologically outdated

5.3.1 Failure Mode and Effect Analysis (FMEA)

Table 5-5 FMEA Table

Process Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s)/ Mechanism(s) of Failure	Occur	Current Process Controls	Detect	RPN	Recommended Action(s)	Action Results			
										Sev	Occ	Det	RPN
Obstacle Avoidance	Does not stop for obstacles	Damage equipment or injury	10	Sensor Failure	2	none	4	80	Sensor test before operating	5	2	1	10
Placing objects	No movement	unavailability of system	7	Connections or power failure	1	none	1	7	routine inspection of psu and cables	4	1	1	4
	Inaccurate positioning	Product damage	8	Belt and pulley	4	none	6	192	installing laser interferometer to measure drift overtime	5	2	2	20
	incorrect positioning	Not retrieving right product	5	software	1	none	9	45	tracking product position after being placed	2	1	1	2

Table 5-6 below, shows the product testing and its results and how the standards will be verified.

Table 5-6 Design Testing and Results

Planned Product Testing					Reporting of Result			
Test #	**Specification / Test Name**	**Method or Procedure**	**Duration (mins)**	**Acceptance Criteria**	**Test Results / Findings**	**Test Results Pass/Fail**	**Test Completed by**	**Notes**
1	MHS 4.11	Length Measurement Using Tape Meter	30	Refer to Page 5 of MHS Specs				
2	4.1.2	Laser Interferometer	120	Within 1/8 inches				
3	Markings	Visual Inspection	10	B13.1.1				
4	Clearance	Visual Inspection	11	B13.1.1				
5	General Construction	Visual Inspection	12	B13.1.2				
6	Cabs	Visual Inspection	13	B13.1.4				
7	Lubrication	Visual Inspection	17	B13.1.5				
8	Brakes	Visual Inspection	30	B13.1.8				
9	Electricals Equipment	Visual Inspection	33	B13.1.9				
10	Hoisting Equipment	Visual Inspection	31	B13.1.10				
11	Inspection	Visual Inspection	120	B13.2.1				
12	Testing	Visual Inspection	171	B13.2.2				
13	Maintenance	Visual Inspection	72	B13.2.3				
14	Belt Inspection and Replacement	Visual Inspection	30	B13.2.7				
15	Load Handling	Visual Inspection	180	B13.3.2				

CHAPTER 6 - RESULTS and DISCUSSION

1. **Design for cost:**

   At the preliminary design stages a budget of $1500 was set for all equipment, shipping, and unforeseen costs. Just over 47% was spent which would make DFC a huge success

2. **Design for manufacturability and assembly:**

   DFMA was proved to be quite challenging. A significant amount of time was spent prototyping due to incorrect tolerances, weak 3D printed components and inadequate time spent designing.

   The number of parts were greatly reduced at the early design stages which made the design modular but due to the ratio of time spent designing to manufacturing, this project would not satisfy DFMA. Further revisions are recommended to be made which would greatly streamline the processes of manufacturing and assembly.

3. **Design for reliability:**

   Preliminary reliability analysis has shown that the system has a theoretical reliability of 71% given that standby units are available. Real world testing determined that this result although conservative was not true. Even at the derated payload capacity the system would not pass any meaningful reliability tests.

   It is recommended for future revisions to use strictly off the shelve parts with high reliability.

CHAPTER 7 - CONCLUSION and FUTURE WORK

As it can be seen from the bill of materials and the budget, this design satisfies greatly with the design of cost. Iterative 3D-printing made it hard to satisfy the DFMA. Due to which, numerous parts had to be redesigned. Due to the lack of standardized parts and industrial level reliable components the system would need to be revised for any field implementations. By using RFID tracking system and conveyor belt, this system also matches the demand of M2M and industry 4.0. The throughput of the system matches the needs of the team but is still not applicable in industrial level. Upon that, for future improvements, obstacle detection can be added for safety purposes. Artificial intelligence can be used for improved arrangement of products. Additionally, HMI and IOT can be introduced for better connectivity and remote operation.

In conclusion, the project has lots of room for improvements and iterative design stages to go through for industrial usage but could also be used to prototyping and demo purposes.

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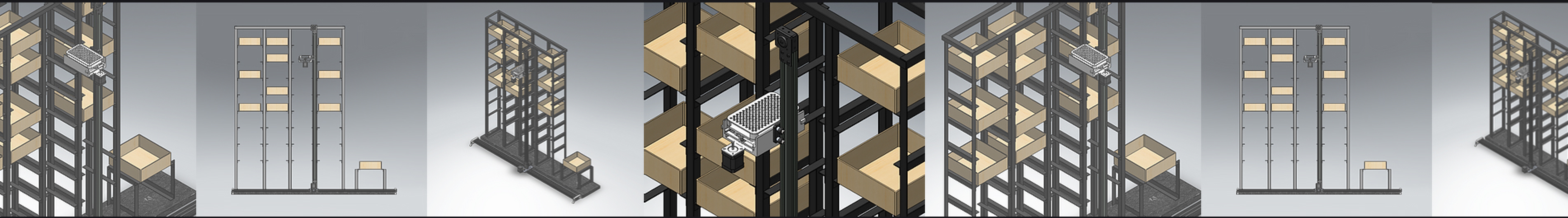
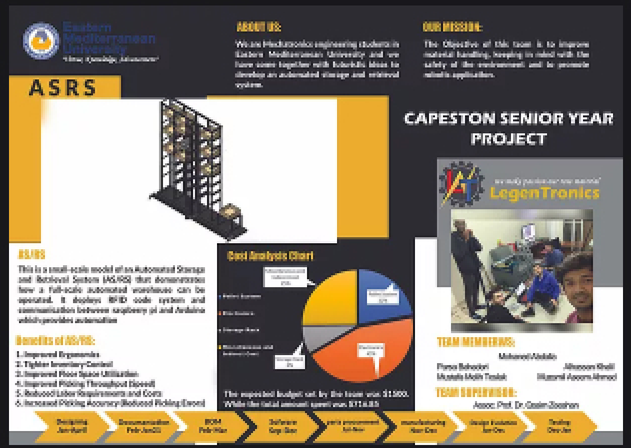
APPENDIX A: ELECTRONIC MEDIA

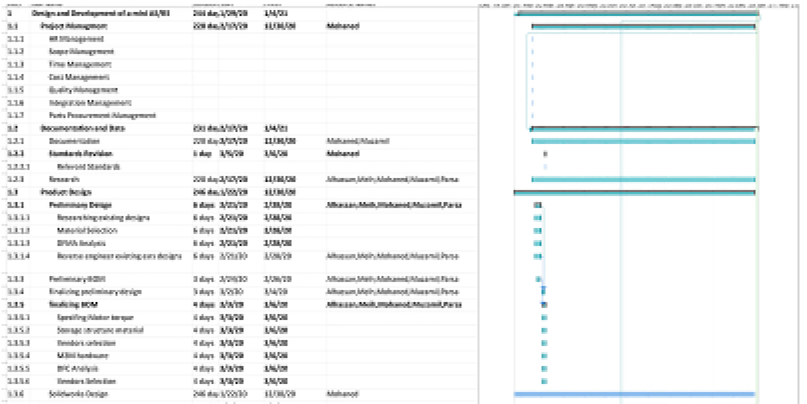
LEGENTRONICS

SMART ASRS





PROJECT TIMELINE



Eastern Mediterranean University
"Virtue, Knowledge, Advancement"

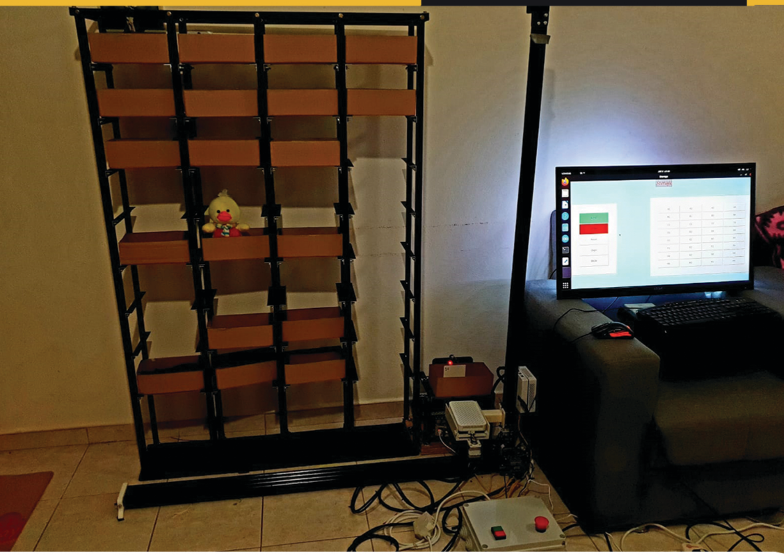
ABOUT US:

We are Mechatronics engineering students in Eastern Mediterranean University and we have come together with futuristic ideas to develop an automated storage and retrieval system.

OUR MISSION:

The Objective of this team is to improve material handling, keeping in mind the safety of the environment and to promote robotic applications.

ASRS



CAPSTONE SENIOR YEAR PROJECT

System Specification

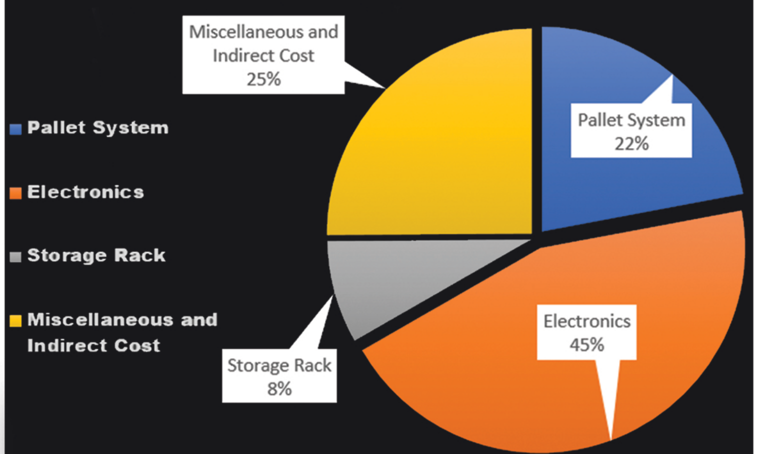
Payload: 350g
Soc: Raspberry-pi 4
RFID module: rc522
Stepper motors: nema 17
Micro controller: Arduino mega

we make passion our raw material
LegenTronics

AS/RS

This is a small-scale model of an Automated Storage and Retrieval System (AS/RS) that demonstrates how a full-scale automated warehouse can be operated. It deploys RFID coding system and communication between the Raspberry-pi and the Arduino which provides machine to machine comminucation.

Cost Analysis Chart



The expected budget set by the team was $1500. While the total amount spent was $716.85

Benefits of AS/RS:

1. Improved Ergonomics
2. Tighter Inventory Control
3. Improved Floor Space Utilization
4. Improved Picking Throughput (Speed)
5. Reduced Labor Requirements and Costs
6. Increased Picking Accuracy (Reduced Picking Errors)

TEAM MEMBERS:

Mohaned Abdalla
Parsa Bahadori
Alhassan Khalil
Mustafa Melih Toslak
Muzamil Aseem Ahmad

TEAM SUPERVISOR:

Assoc. Prof. Dr. Qasim Zeeshan

Designing Jan-April → Documantation Feb-Jan21 → BOM Feb-Mar → Sofware Sep-Dec → Parts procurement Jul-Nov → Manufacturing Nov-Dec → Design Evolution Jan-Dec → Testing Dec-Jan

APPENDIX B: CONSTRAINTS

Constraints are conditions that we need to happen or would like to happen with a design. There were some constraints faced when this project was being designed and planned.

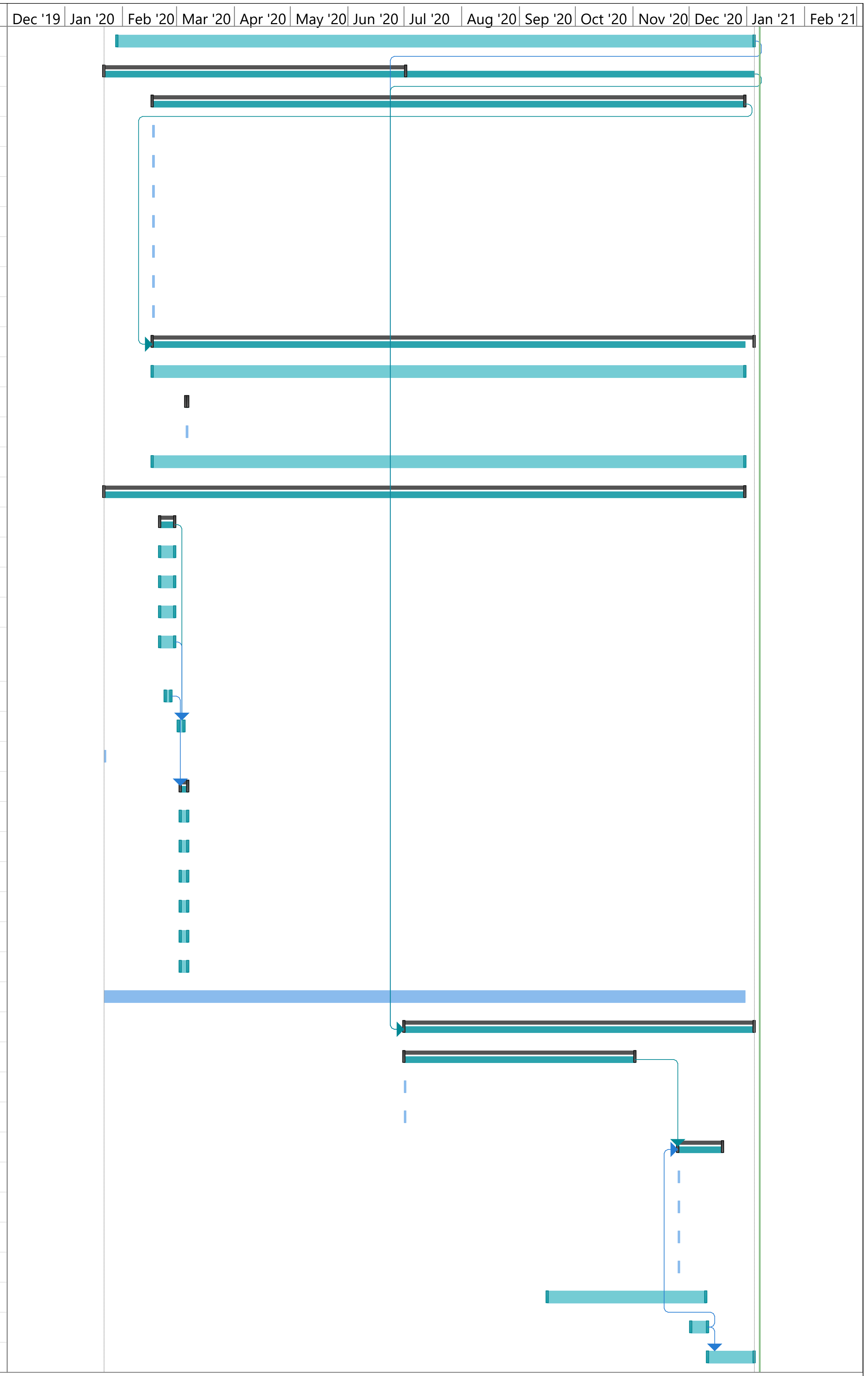
- Cost: Total cost of the project must be taken care for, as this project is to be done by a group of university students and it must be financially stable for every member in the team.
- Time: The time to perform this project is fairly enough but can be a major problem as a group of students, there may be other exams to work for and some shipping may delay due to transits and according to the latest news, lock down of countries and cities due to corona virus.
- Safety: It is an important measure for the team and the consumer/customer/professor so that it does not injure anyone and to do this, the team must use the safety equipment and fix the joints properly and by solving the mathematical problems without any errors.
- Sustainability: The sustainability of a project can play a major role in the long-term strategy of a company, and can often affect a project. There are three parts of sustainability: social, environmental, and economical. This project is quite sustainable as it is socially and environmentally friendly and quite economical.
- Shipping: Since this project is taking place in the Northern Republic of Turkish Cyprus, most of the electrical equipment is being shipped, due to the lack of availability. However, the cargo shipment will consume extra time and in addition, shipping to TRNC is quite expensive as the TRNC government has imposed high taxes on such equipment. Moreover, lock down of countries and cities due to corona virus may also delay shipment. Due to this, the team may also face the limitation of materials and components.

APPENDIX C: STANDARDS

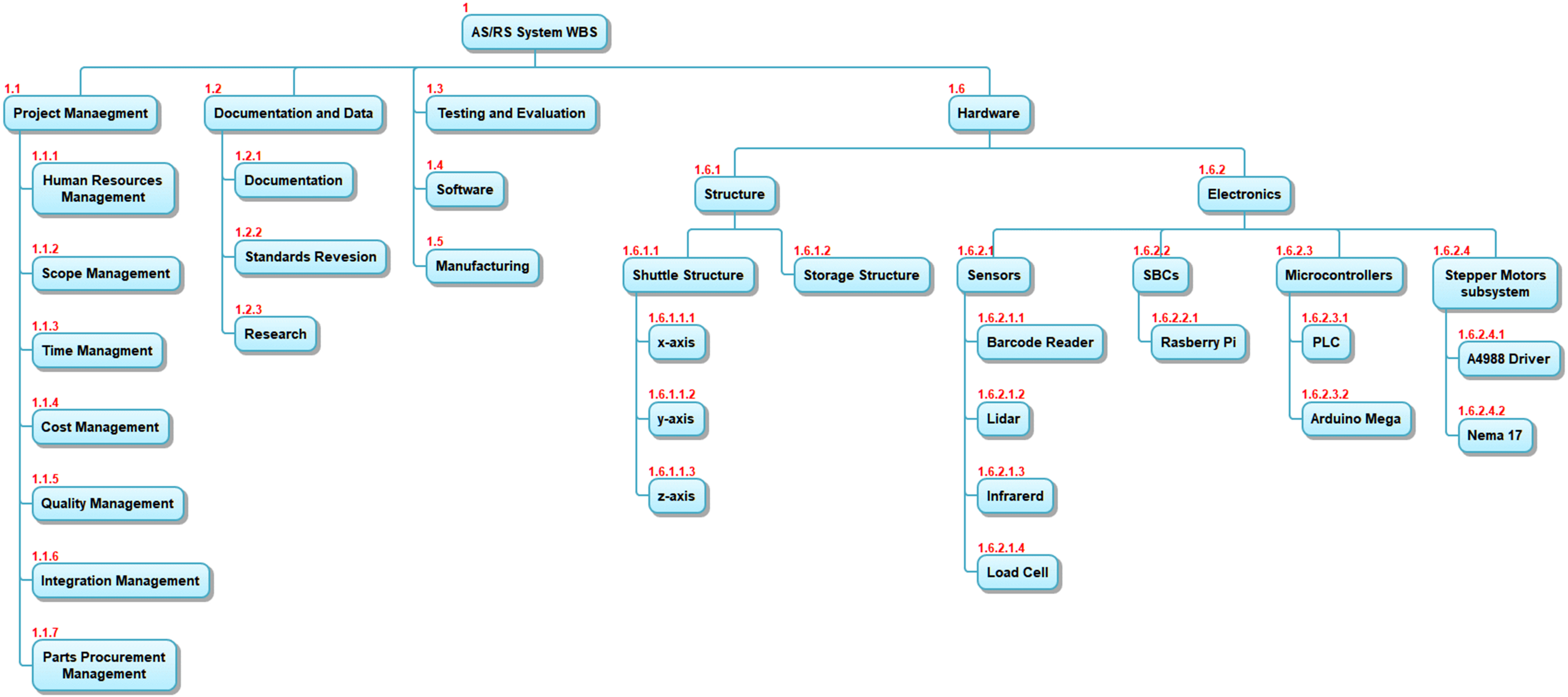
Application Area	Standards	Remark
AS/RS	ASME B30.13-2011 Storage/Retrieval	Partially followed due to the fact the standard specifications that can only be applied to full size AS/RS application.
Software	ANSI/ISA - S5.1-1984 (R1992)	Used for electrical component symbols in circuits
	ISO 128	
Reliability	IEEE STD 493-1997	Reliability of the power system
Material Handling	NIST Material Handling 1998	Partially followed due to the fact that the paper is technologically outdated
Mechanical	ISO 17396:2017	GT2 belts
	20x40-5	Aluminum rods
	NEMA	Stepper motors
	AMSS	3D - Printing
	ISO 262: 1998	Screws, Nuts, Washers
Electrical	IEEE std 1855	Arduino
	RoHS3 & REACH	Raspberry Pi
	BS 7671:2008	Wiring Regulations
	ISO 13850 / 4.4.4	Emergency Switch
	ISO 15459	RFID

APPENDIX D: PROJECT TIMELINE

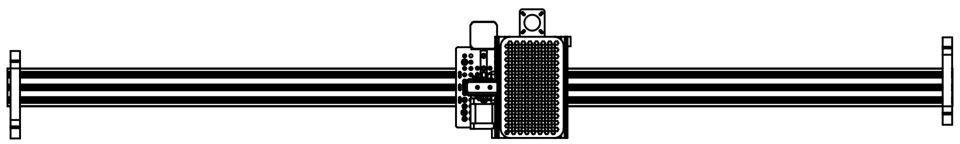
ID	WBS	Task Name	Duration	Start	Finish	Resource Names
1	1	Design and Development of a mini AS/RS	244 days	29-01-20	04-01-21	
2	2	**Capstone 1**	**116 days**	**22-01-20**	**01-07-20**	
3	2.1	**Project Managment**	**228 days**	**17-02-20**	**30-12-20**	**Mohaned**
4	2.1.1	HR Management				
5	2.1.2	Scope Management				
6	2.1.3	Time Management				
7	2.1.4	Cost Management				
8	2.1.5	Quality Management				
9	2.1.6	Integration Management				
10	2.1.7	Parts Procurement Management				
11	2.2	**Documentation and Data**	**231 days**	**17-02-20**	**04-01-21**	
12	2.2.1	Documentation	228 days	**17-02-20**	**30-12-20**	Mohaned,Muzzamil
13	2.2.2	**Standards Revision**	**1 day**	**05-03-20**	**06-03-20**	**Mohaned**
14	2.2.2.1	Relevant Standards				
15	2.2.3	Research	228 days	**17-02-20**	**30-12-20**	Alhassan,Meih,Mohaned,Muzzamil,Parsa
16	2.3	**Product Design**	**246 days**	**22-01-20**	**30-12-20**	
17	2.3.1	**Conceptual Deisgn**	**6 days**	**21-02-20**	**28-02-20**	**Alhassan,Meih,Mohaned,Muzzamil,Parsa**
18	2.3.1.1	Researching existing designs	6 days	**21-02-20**	**28-02-20**	
19	2.3.1.2	Material Selection	6 days	**21-02-20**	**28-02-20**	
20	2.3.1.3	DFMA Analysis	6 days	**21-02-20**	**28-02-20**	
21	2.3.1.4	Reverse engineer existing asrs designs	6 days	21-02-20	28-02-20	Alhassan,Meih,Mohaned,Muzzamil,Parsa
22	2.3.2	Preliminary BOM	3 days	24-02-20	26-02-20	Alhassan,Meih,Mohaned,Muzzamil,Parsa
23	2.3.3	Finalizing preliminary design	3 days	02-03-20	04-03-20	Alhassan,Meih,Mohaned,Muzzamil,Parsa
24	2.3.4	Detail Design				
25	2.3.5	**Finalizing BOM**	**4 days**	**03-03-20**	**06-03-20**	**Alhassan,Meih,Mohaned,Muzzamil,Parsa**
26	2.3.5.1	Specifing Motor torque	4 days	**03-03-20**	**06-03-20**	
27	2.3.5.2	Storage structure material	4 days	**03-03-20**	**06-03-20**	
28	2.3.5.3	Vendors selection	4 days	**03-03-20**	**06-03-20**	
29	2.3.5.4	M2M hardware	4 days	**03-03-20**	**06-03-20**	
30	2.3.5.5	DFC Analysis	4 days	**03-03-20**	**06-03-20**	
31	2.3.5.6	Vendors Selection	4 days	**03-03-20**	**06-03-20**	
32	2.3.6	Solidworks Design	246 days	22-01-20	30-12-20	Mohaned
33	3	**Capstone 2**	**134 days**	**01-07-20**	**04-01-21**	
34	3.1	**Part Procuremnet**	**89 days**	**01-07-20**	**01-11-20**	**Alhassan,Meih,Mohaned,Muzzamil,Parsa**
35	3.1.1	Online Orders				
36	3.1.2	Sourcing Local parts				
37	3.2	**Manufacturing**	**18 days**	**25-11-20**	**18-12-20**	
38	3.2.1	Prototype Development				
39	3.2.2	Shuttle Assembly				
40	3.2.3	3D printing				
41	3.2.4	Storage Assembly				
42	3.3	Software Development	61 days	16-09-20	09-12-20	Alhassan
43	3.4	Applying Standards	7 days	02-12-20	10-12-20	Alhassan,Meih,Mohaned,Muzzamil,Parsa
44	3.5	Testing and Evalution	17 days	11-12-20	04-01-21	Alhassan,Meih,Mohaned,Muzzamil,Parsa

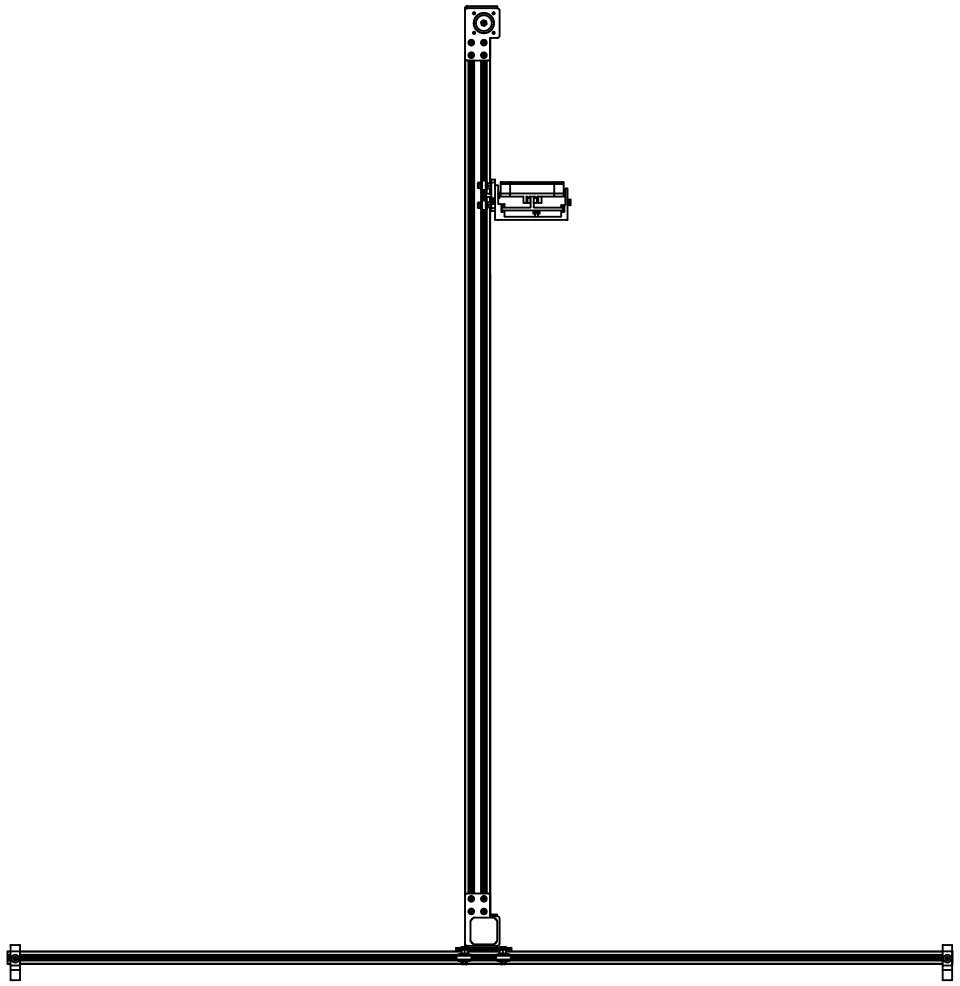


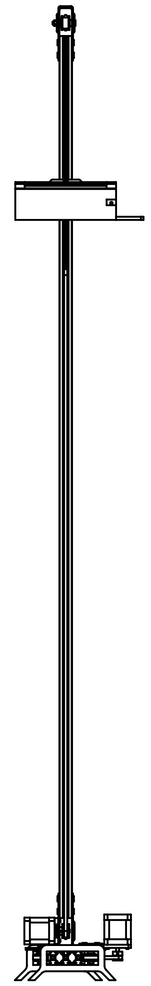
APPENDIX E: WORK BREAKDOWN STRUCTURE


1
AS/RS System WBS
1.1
Project Manaegment
1.1.1
Human Resources Management
1.1.2
Scope Management
1.1.3
Time Managment
1.1.4
Cost Management
1.1.5
Quality Management
1.1.6
Integration Management
1.1.7
Parts Procurement Management
1.2
Documentation and Data
1.2.1
Documentation
1.2.2
Standards Revesion
1.2.3
Research
1.3
Testing and Evaluation
1.4
Software
1.5
Manufacturing
1.6
Hardware
1.6.1
Structure
1.6.1.1
Shuttle Structure
1.6.1.1.1
x-axis
1.6.1.1.2
y-axis
1.6.1.1.3
z-axis
1.6.1.2
Storage Structure
1.6.2
Electronics
1.6.2.1
Sensors
1.6.2.1.1
Barcode Reader
1.6.2.1.2
Lidar
1.6.2.1.3
Infrarerd
1.6.2.1.4
Load Cell
1.6.2.2
SBCs
1.6.2.2.1
Rasberry Pi
1.6.2.3
Microcontrollers
1.6.2.3.1
PLC
1.6.2.3.2
Arduino Mega
1.6.2.4
Stepper Motors subsystem
1.6.2.4.1
A4988 Driver
1.6.2.4.2
Nema 17

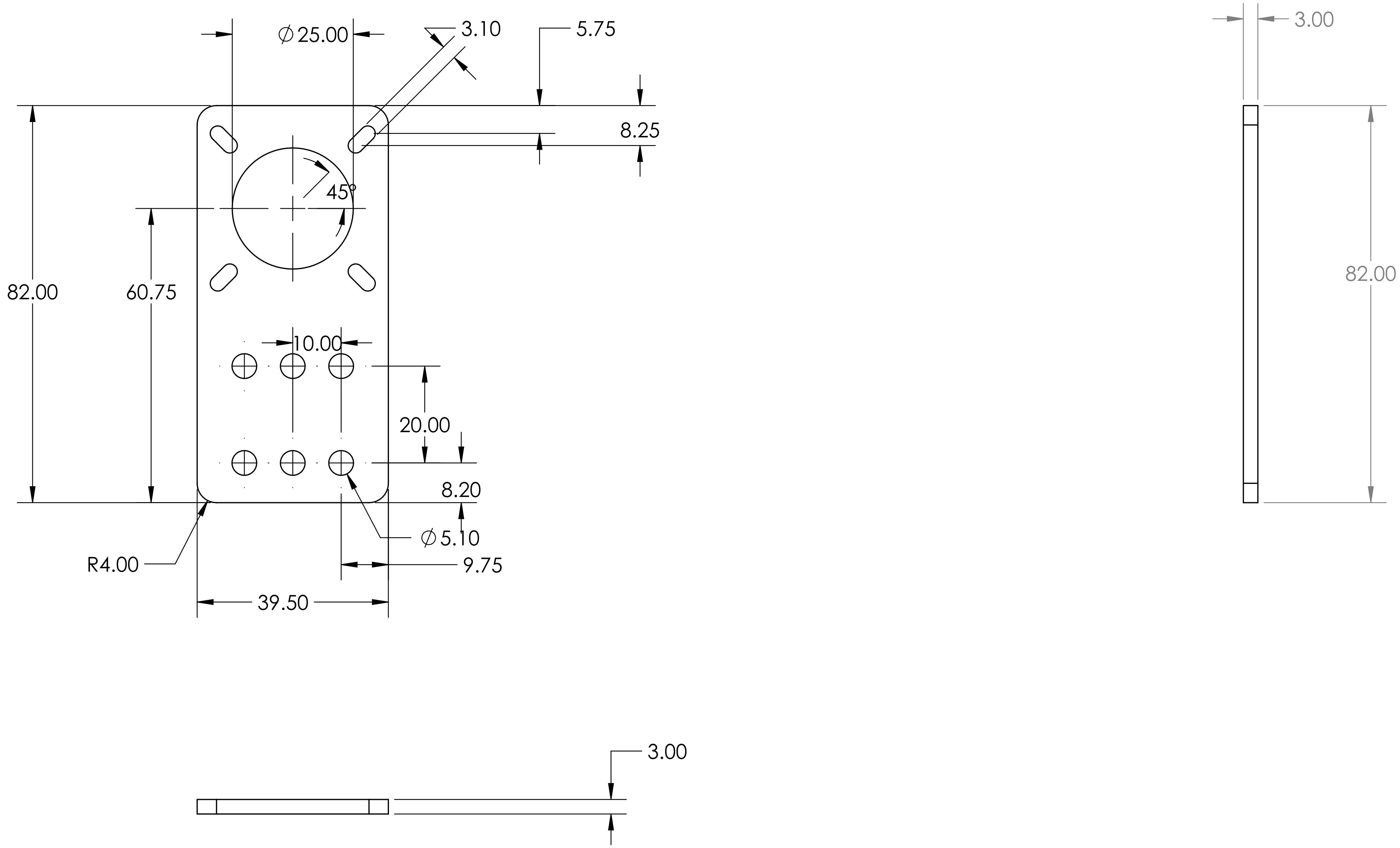
APPENDIX F: ENGINEERING DRAWINGS







UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 3
	NAME	SIGNATURE	DATE	TITLE:	
DRAWN	Mohaned			SHUTTLE ASSEMBLY	
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL:	DWG NO. SH	A3
			WEIGHT:	SCALE: 1:12	SHEET 1 OF 1



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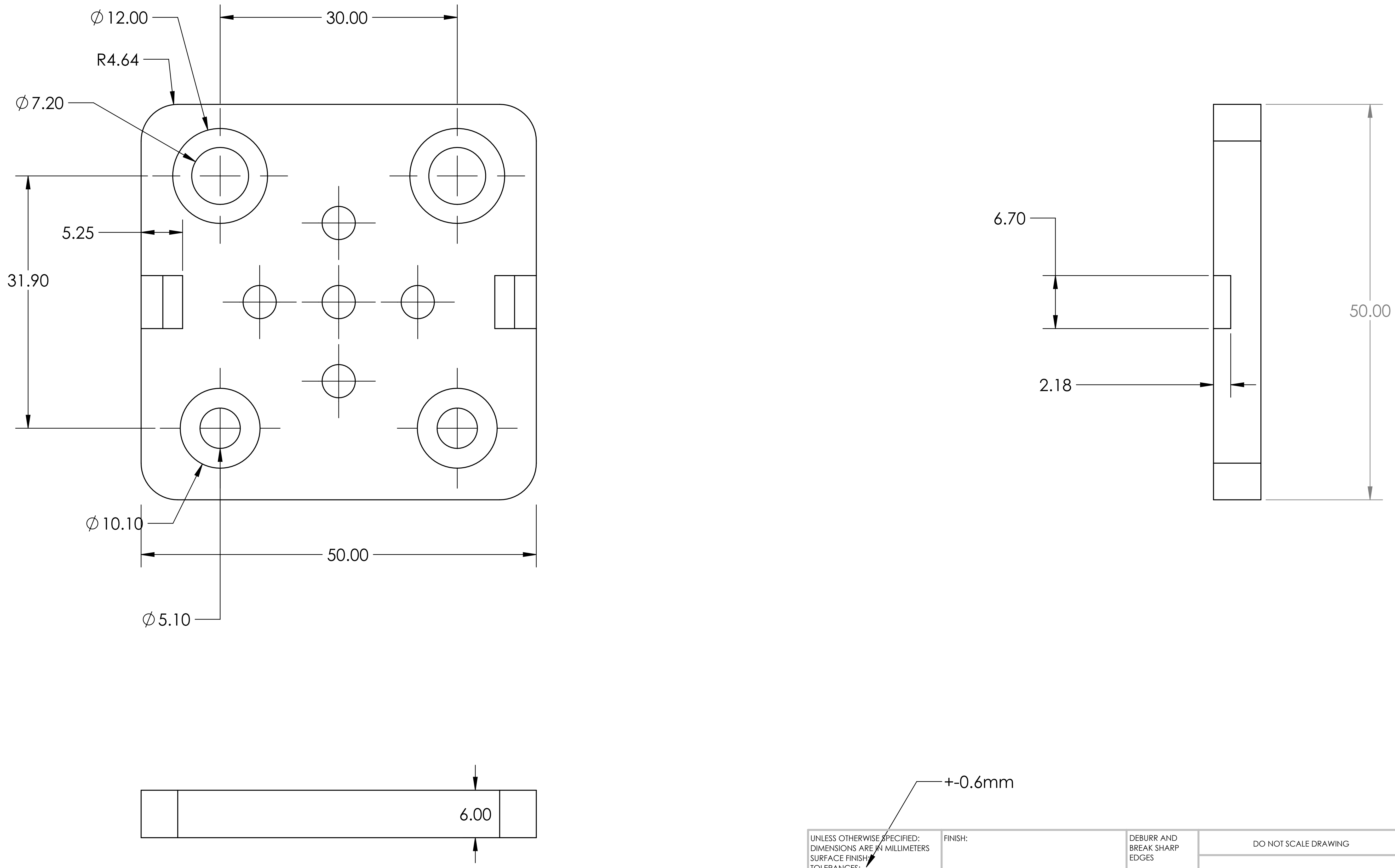
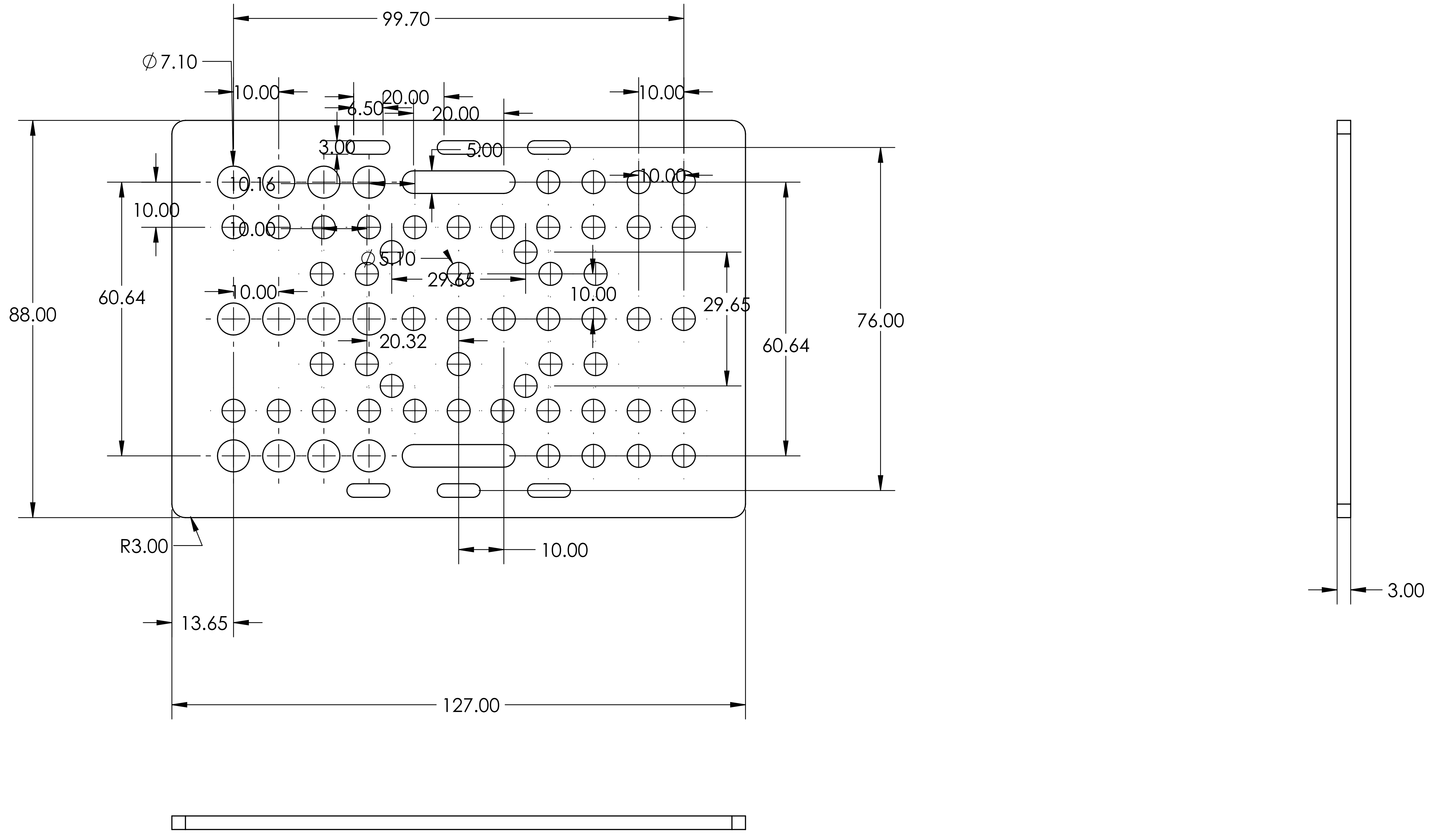
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:			DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			TITLE: SH-07	
DRAWN							
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL: ABS		DWG NO. SH-07	A3
				WEIGHT:		SCALE:1:1	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE	TITLE:	
DRAWN				SH-08	
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL: PLA	DWG NO. SH-08	A3
			WEIGHT:	SCALE:2:1	SHEET 1 OF 1



+-0.6mm

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

V-SLOT GANTRY PLATE

MATERIAL:
Aluminum

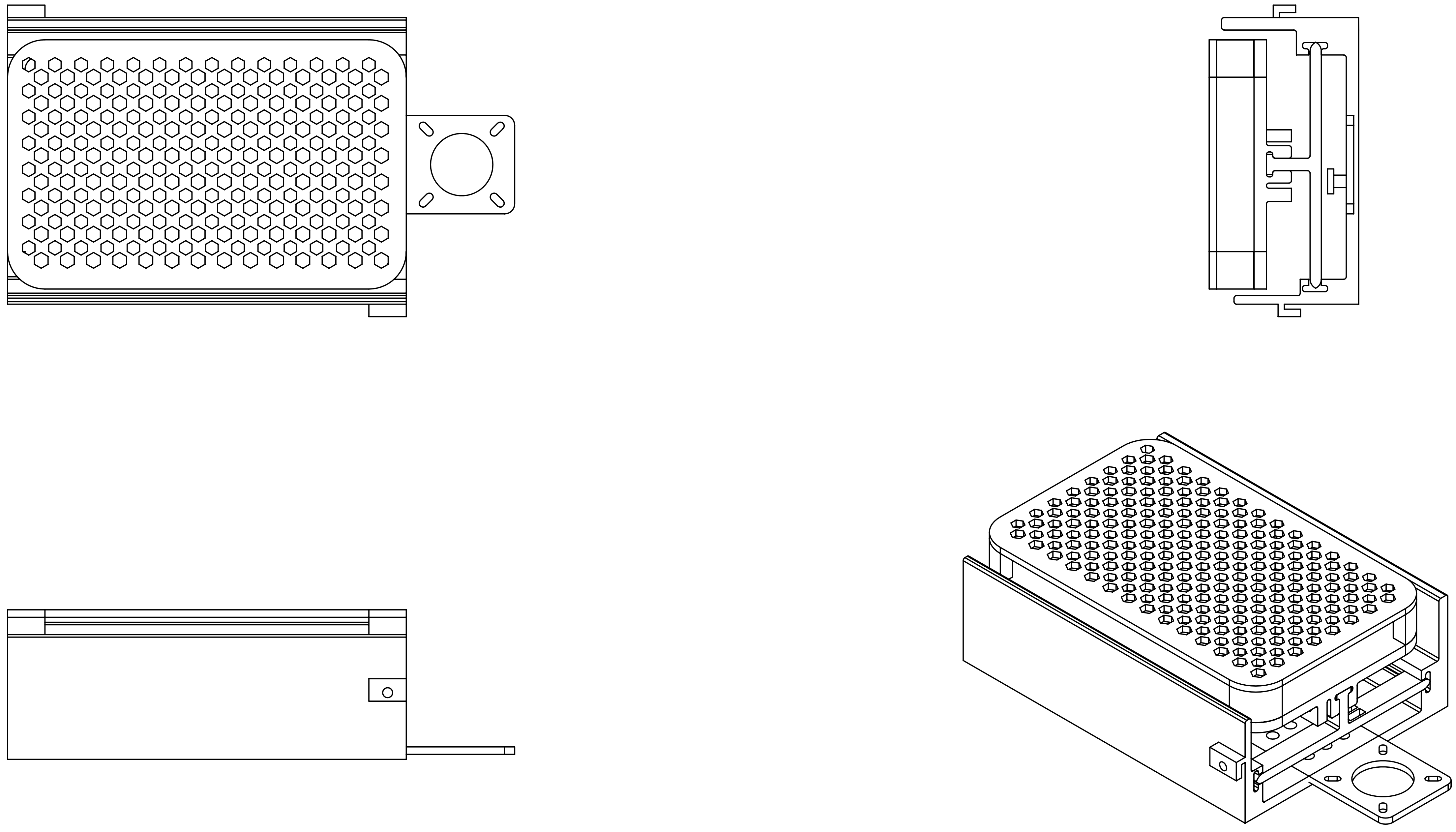
DWG NO.
SH-09

A3

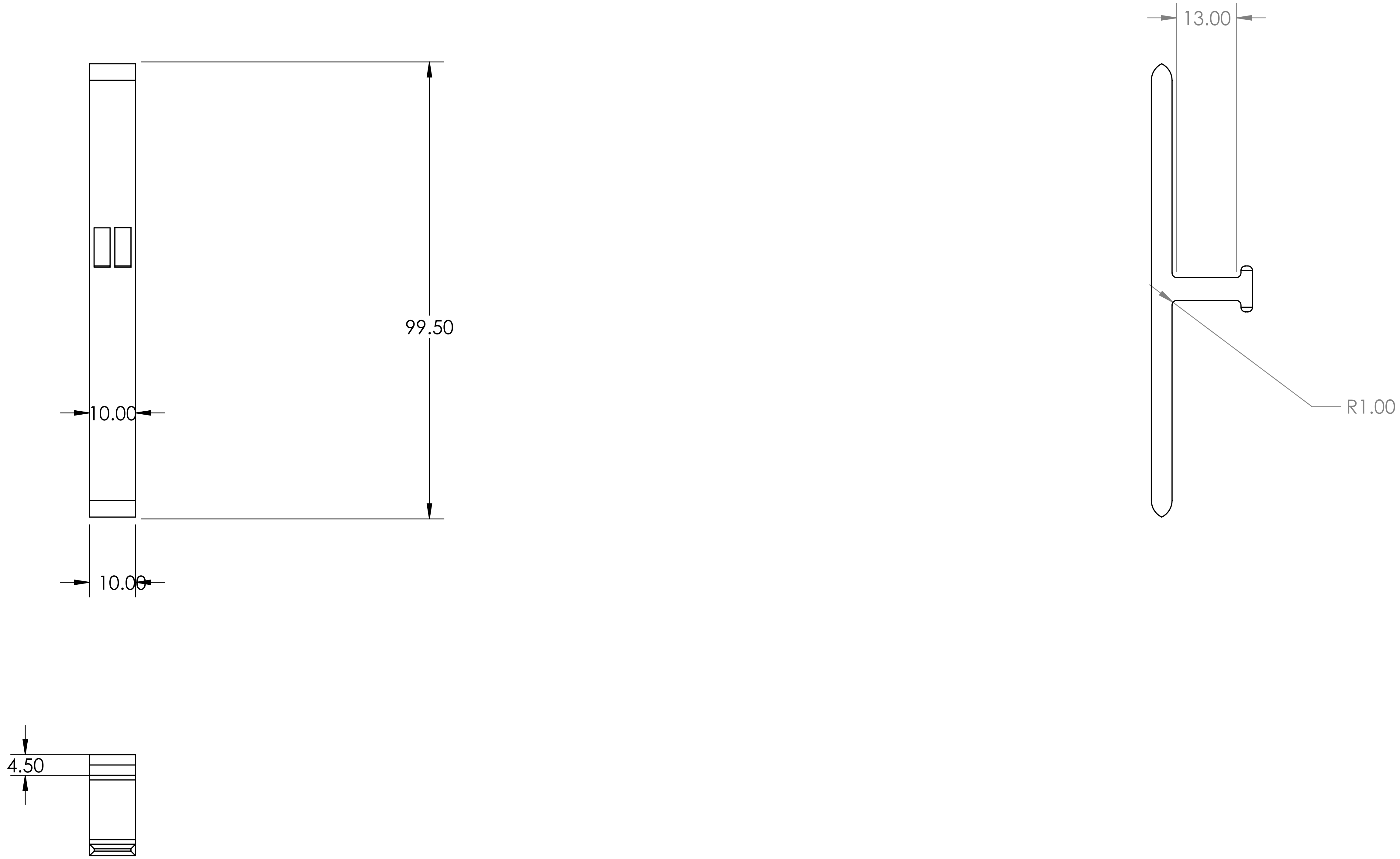
WEIGHT:

SCALE:1:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	
	NAME	SIGNATURE	DATE		TITLE:	
DRAWN	MOHANED				Z-AXIS	
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL:	DWG NO. SH-11	A3
				WEIGHT:	SCALE:1:2	SHEET 1 OF 1



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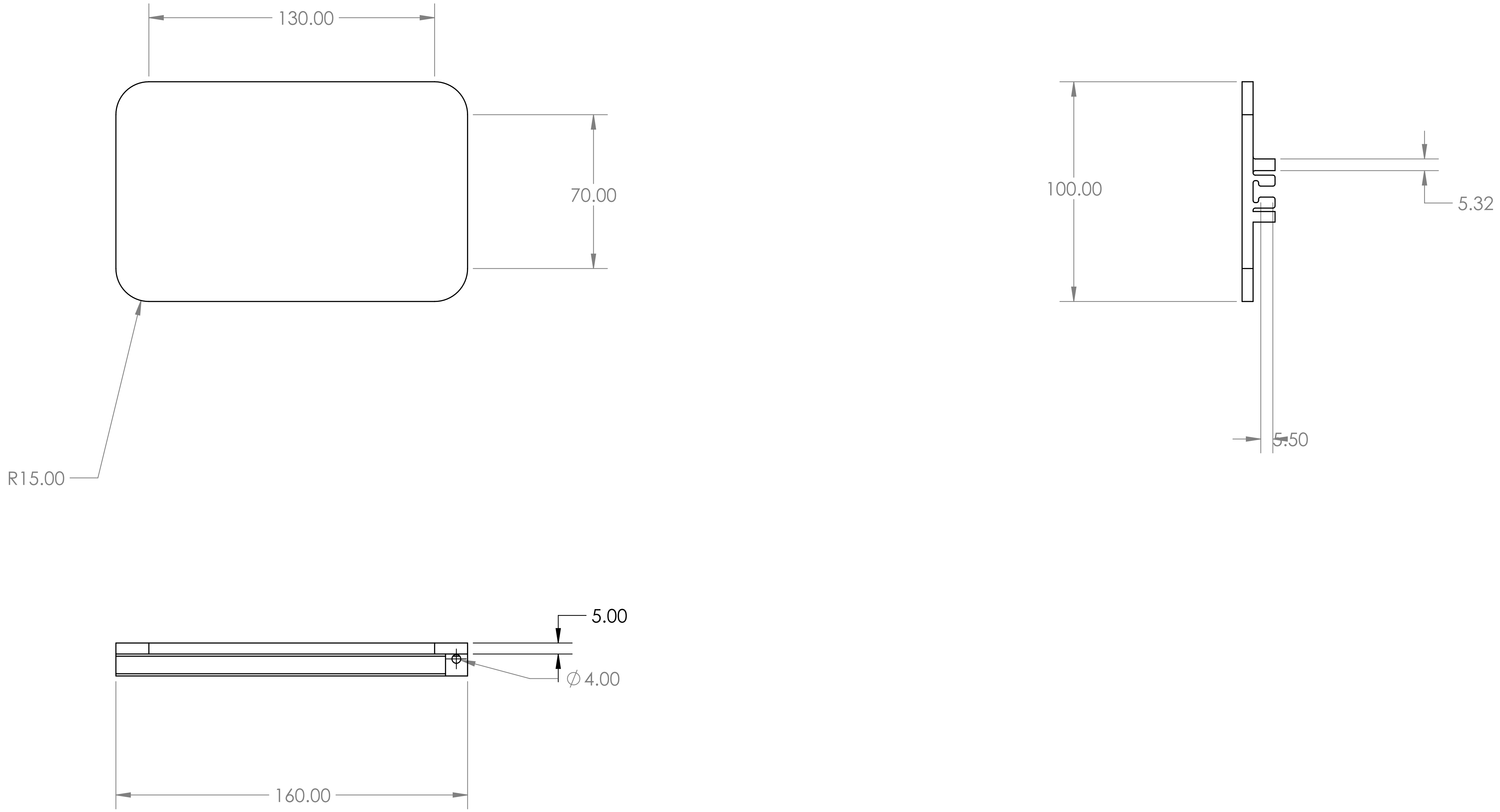
	NAME	SIGNATURE	DATE		TITLE:	
DRAWN	MOHANED				PART A	
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL: PLA	DWG NO. SH-11A	A3
				WEIGHT:	SCALE:1:1	SHEET 1 OF 1



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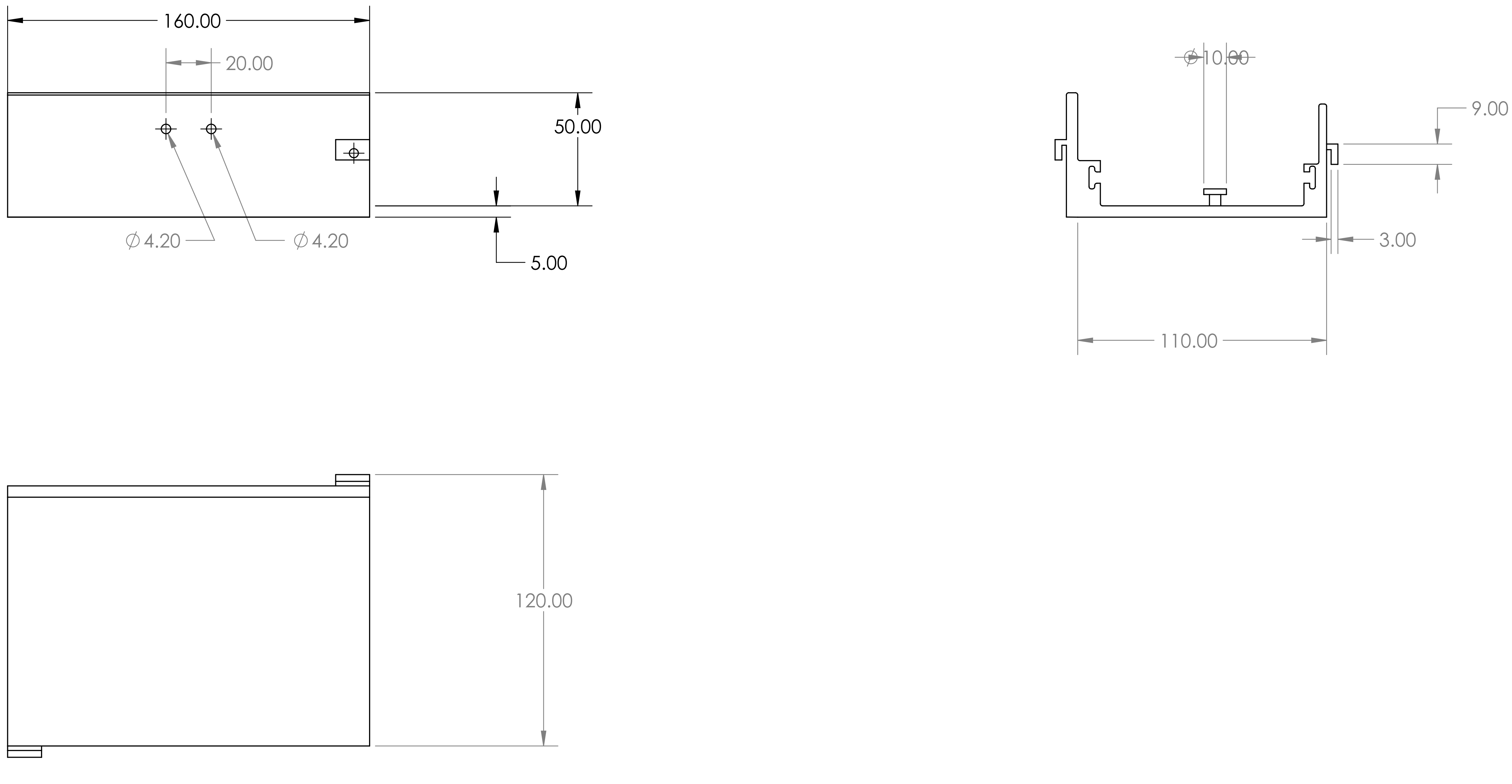
	NAME	SIGNATURE	DATE	TITLE:	
DRAWN	MOHANED			PART B	
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL: PLA	DWG NO. SH-11B	A3
			WEIGHT:	SCALE:1:2	SHEET 1 OF 1



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SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	MOHANED		
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

PART C

MATERIAL: PLA

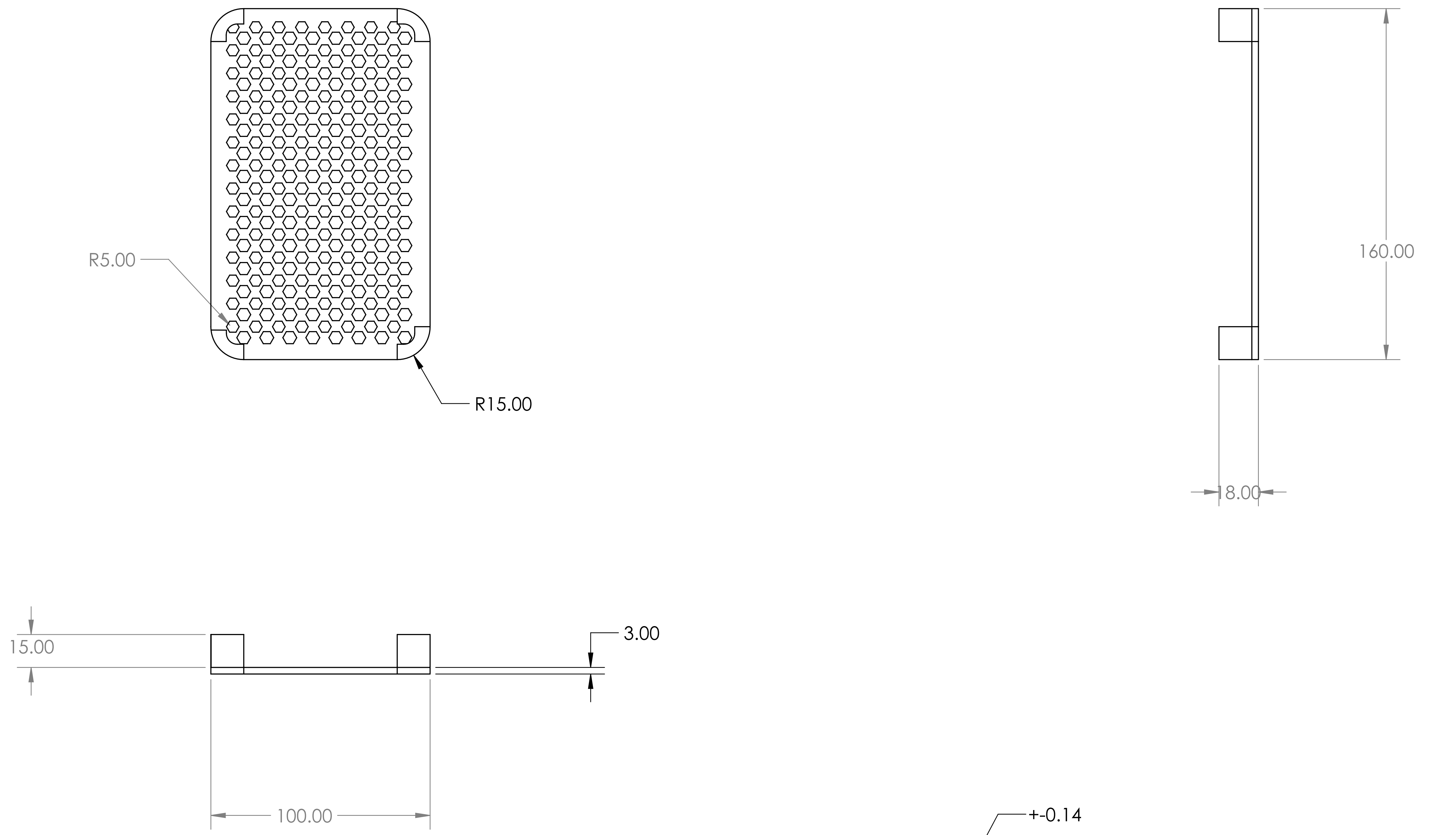
DWG NO. SH-11C

A3

WEIGHT:

SCALE:1:2

SHEET 1 OF 1



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SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	MOHANED		
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

PART D

MATERIAL: PLA

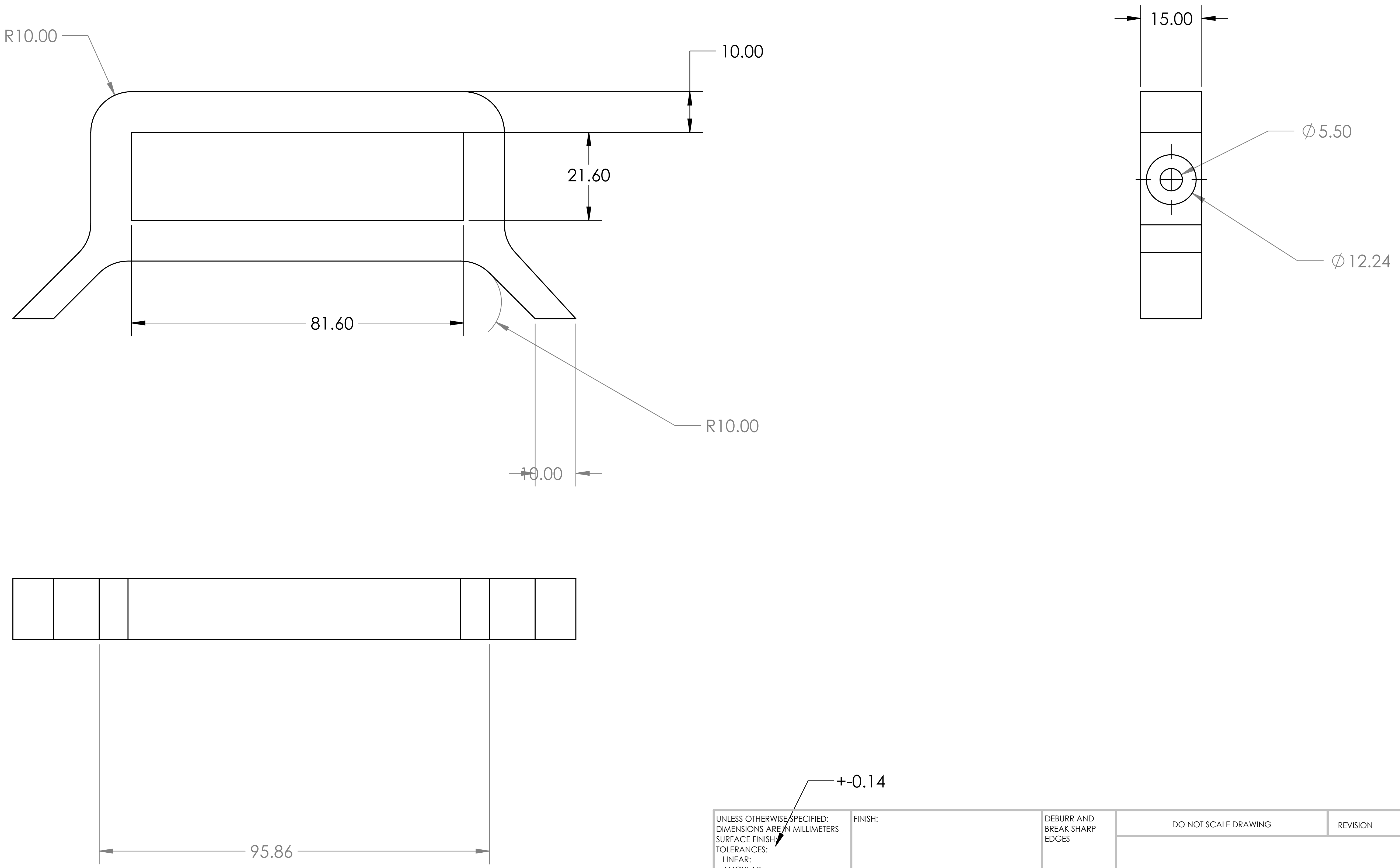
DWG NO. SH-11D

A3

WEIGHT:

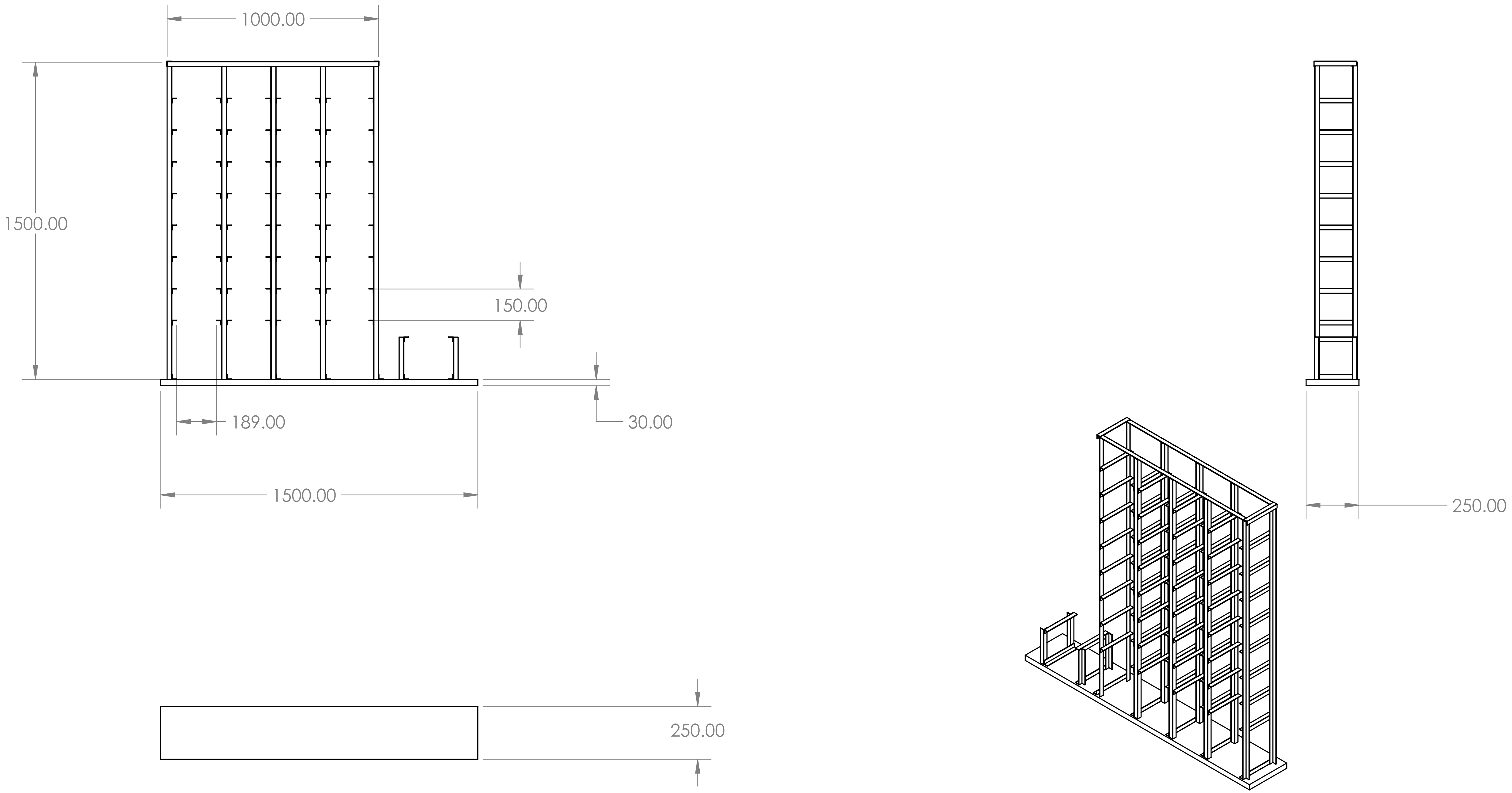
SCALE:1:2

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE	
DRAWN	MOHANED			TITLE: STAND
CHK'D				
APPV'D				
MFG				
Q.A			MATERIAL: PLA	DWG NO. SH-13 — A3
			WEIGHT:	SCALE:1:1 — SHEET 1 OF 1



+-1.4

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	MOHANED		
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: STORAGE STRUCTURE ASSEMBLY

MATERIAL:

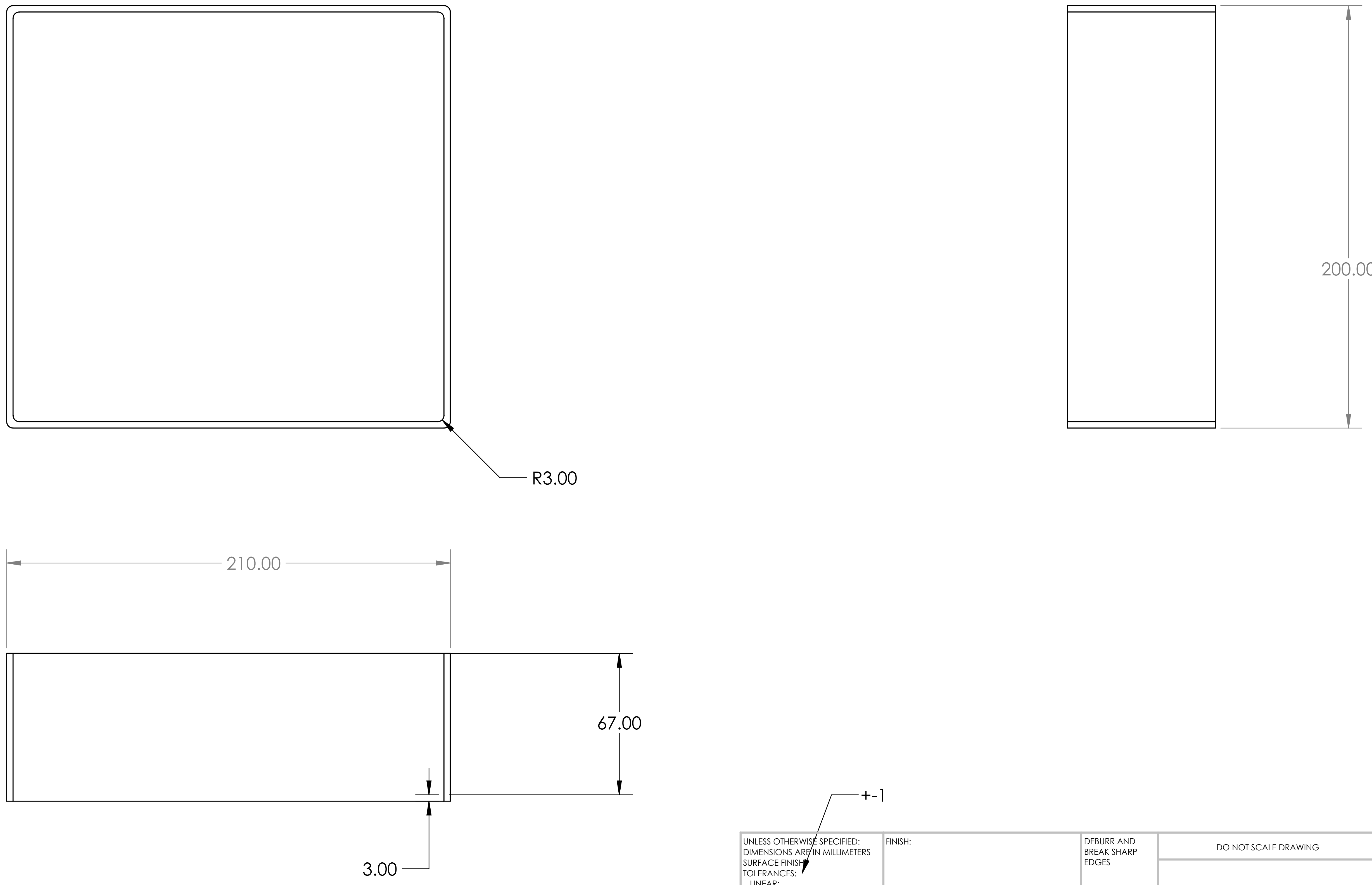
DWG NO. ST

A3

WEIGHT:

SCALE:1:20

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

BIN

MATERIAL: CARDBOARD

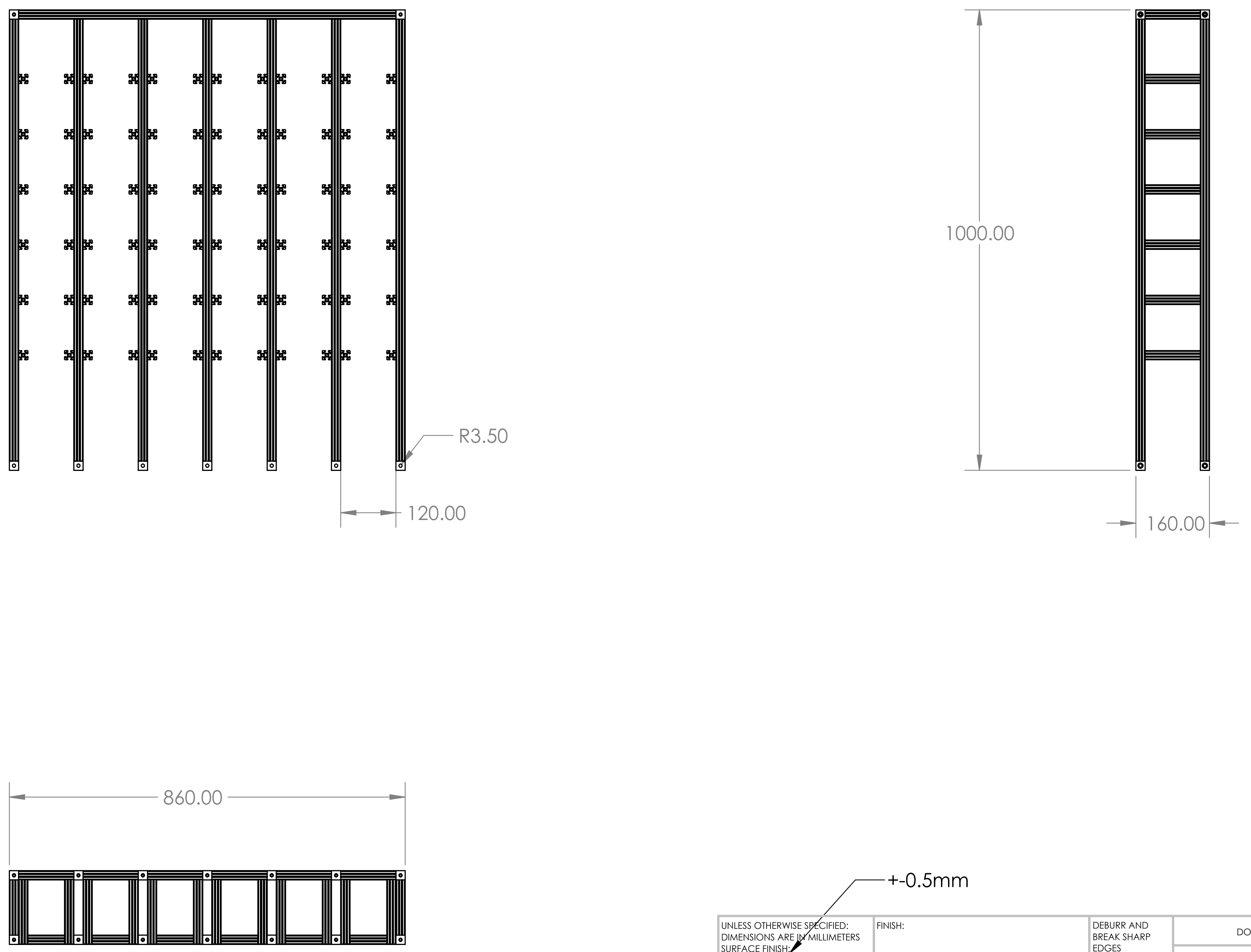
DWG NO. ST-04

A3

WEIGHT:

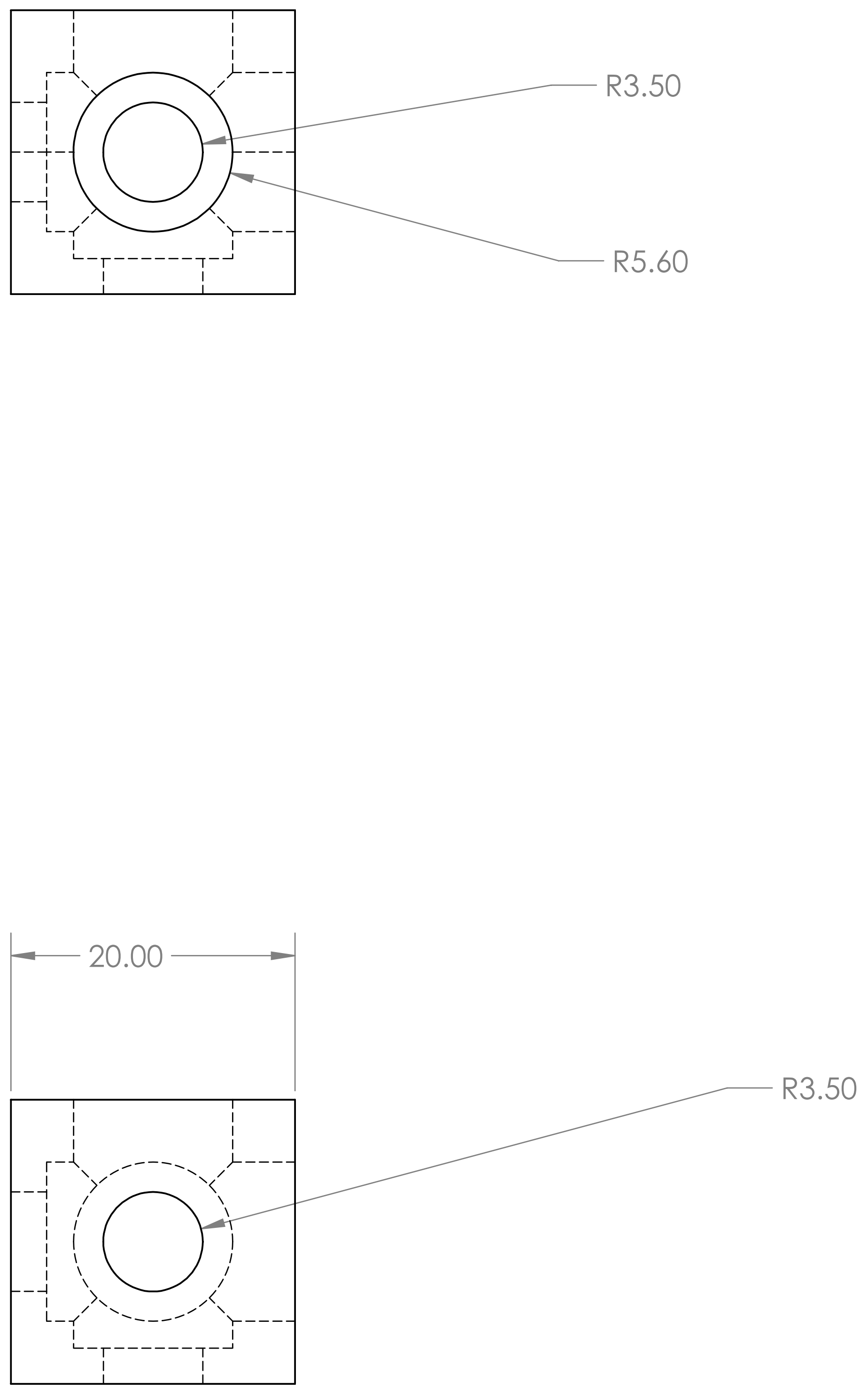
SCALE:1:2

SHEET 1 OF 1

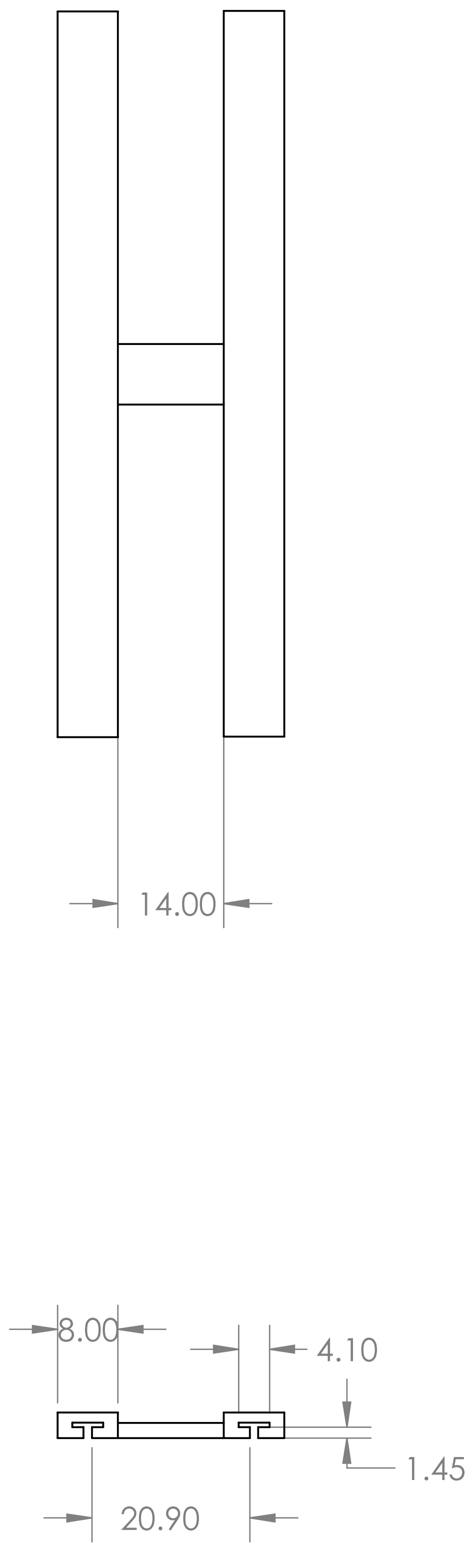


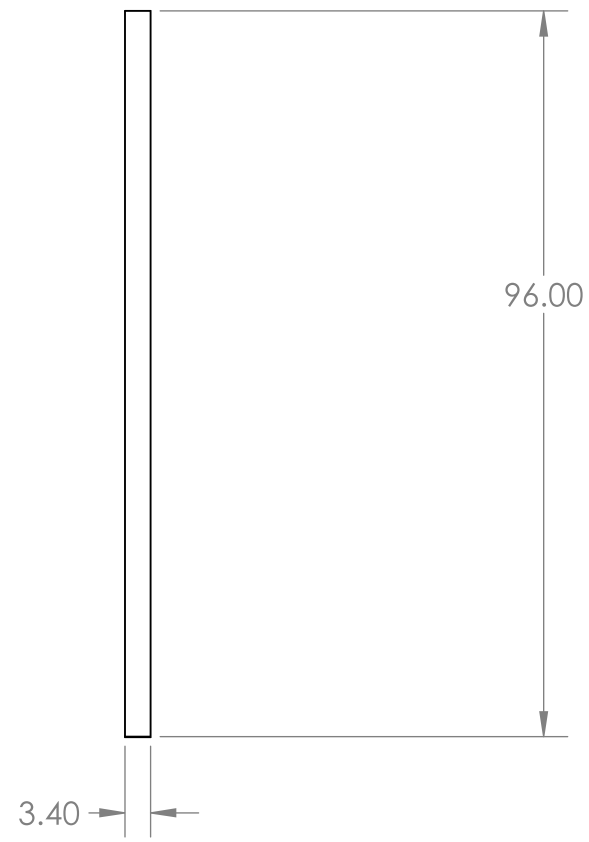
+-0.5mm

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:			DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE		TITLE:	
DRAWN					Storage	
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL: 6063-T6 Aluminum	DWG NO. 161-1	A3
				WEIGHT:	SCALE:1:10	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME / SIGNATURE / DATE		TITLE: CORNER CONNECTOR	
DRAWN				
CHK'D				
APPV'D				
MFG				
Q.A		MATERIAL: ABS	DWG NO. 261-1	A3
		WEIGHT:	SCALE:2:1	SHEET 1 OF 1





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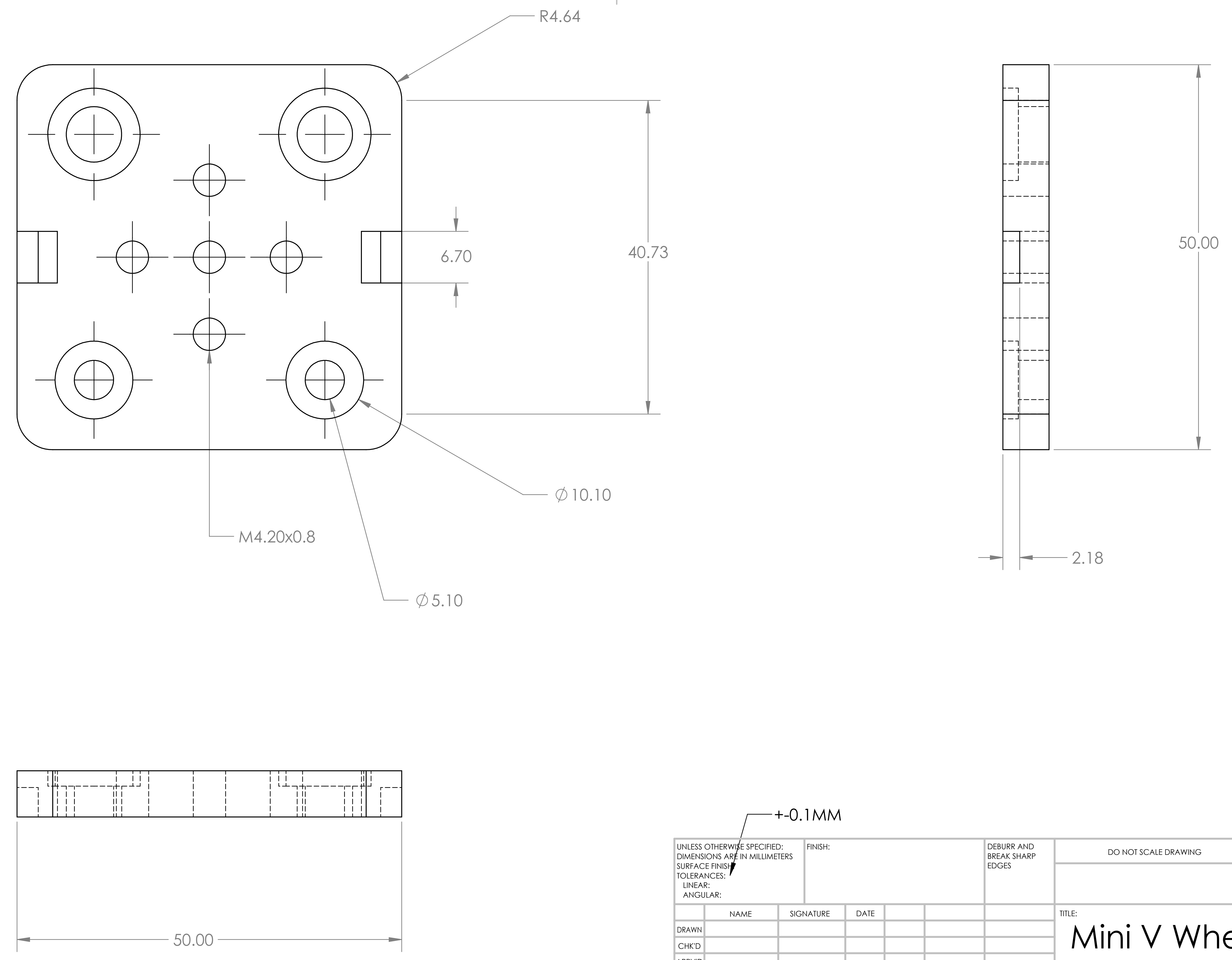
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:			DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE		TITLE: fork	
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL: ABS	DWG NO. 261-Z3	A3
				WEIGHT:	SCALE:1:1	SHEET 1 OF 1



+-0.1MM

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Mini V Wheel Plate

MATERIAL: ABS

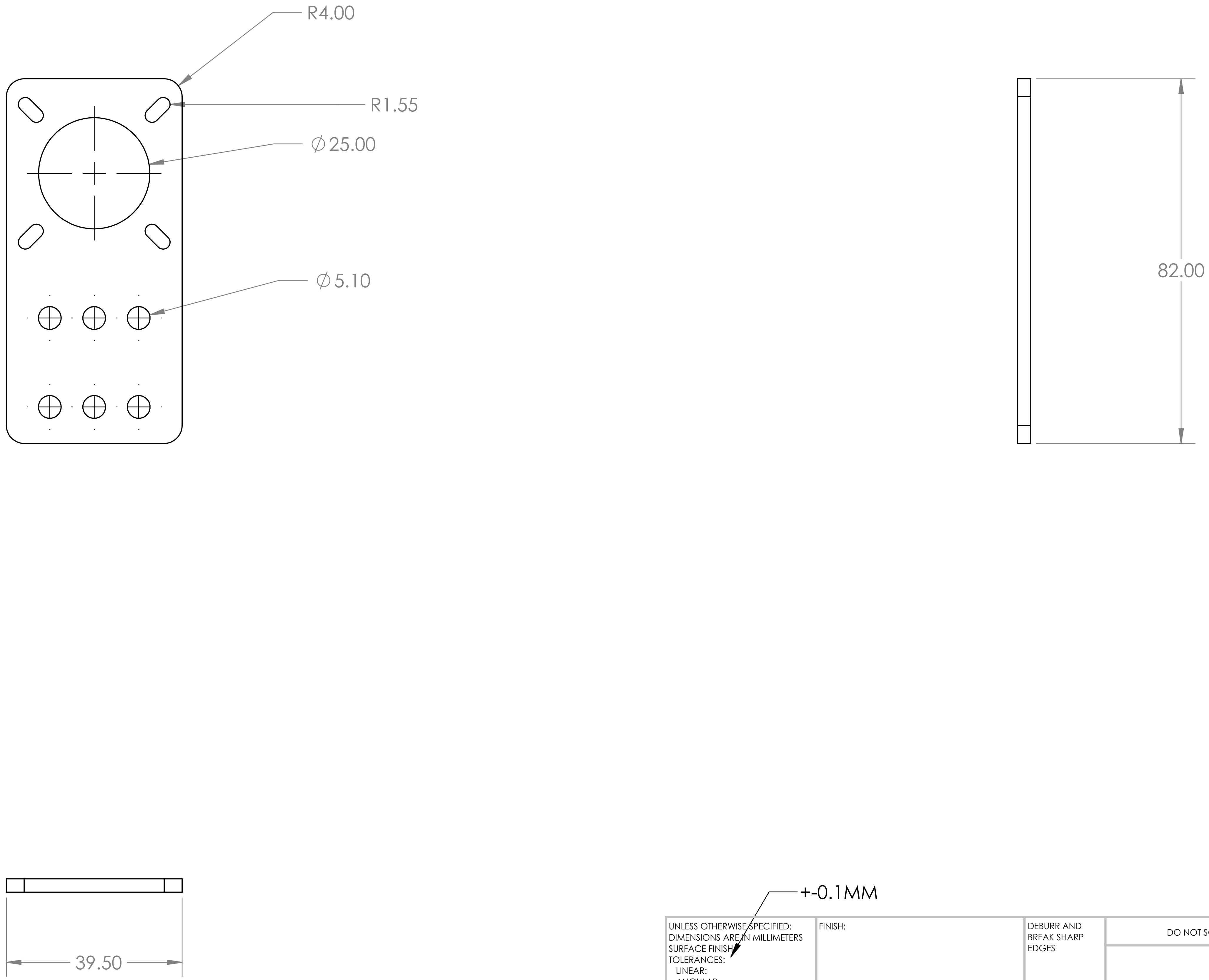
DWG NO. 261-18

A3

WEIGHT:

SCALE:2:1

SHEET 1 OF 1



+-0.1MM

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Motor Mount Plate Nema 17

MATERIAL: ABS

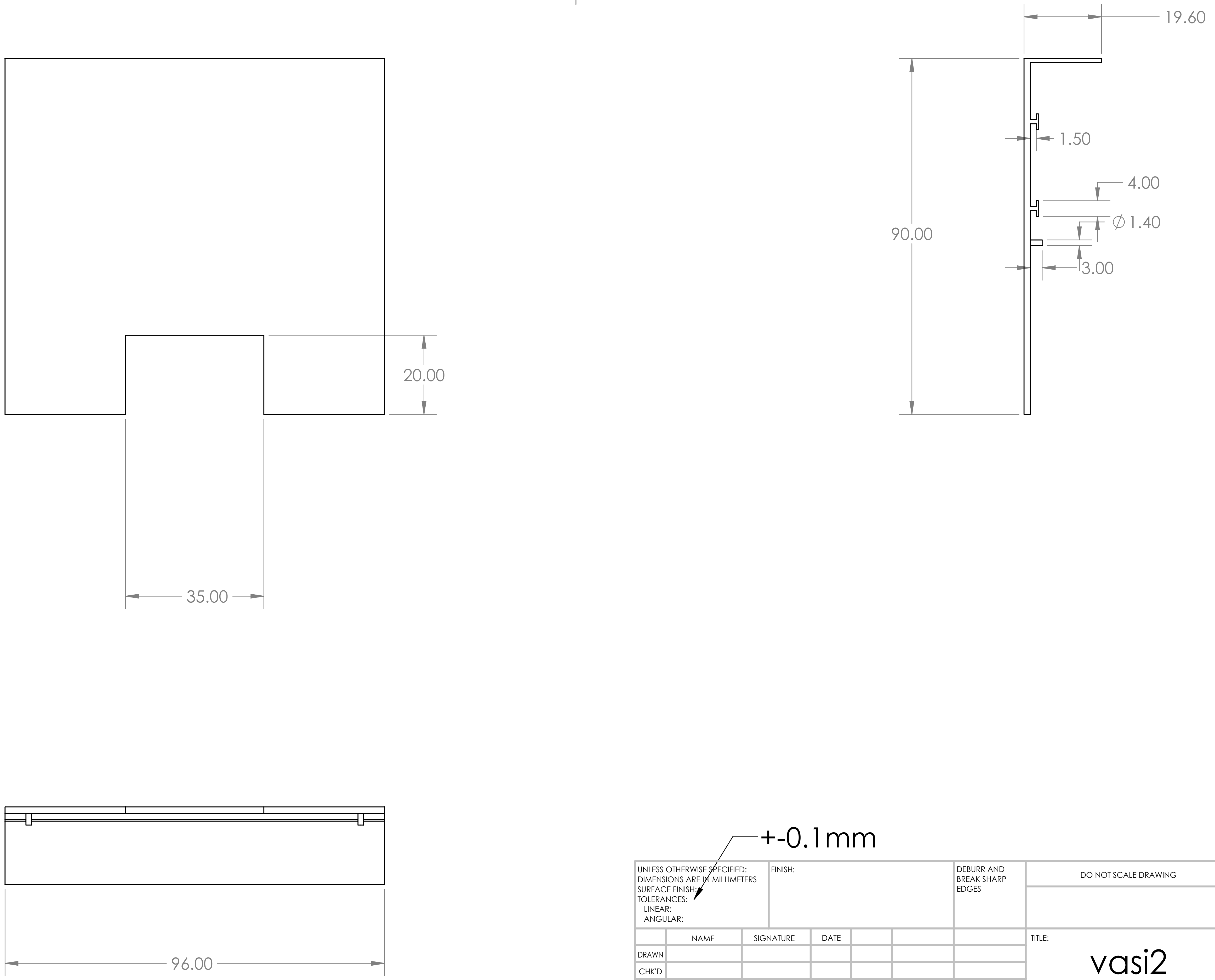
DWG NO. 216-17

A3

WEIGHT:

SCALE:1:1

SHEET 1 OF 1



+-0.1mm

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: vasi2

MATERIAL: ABS

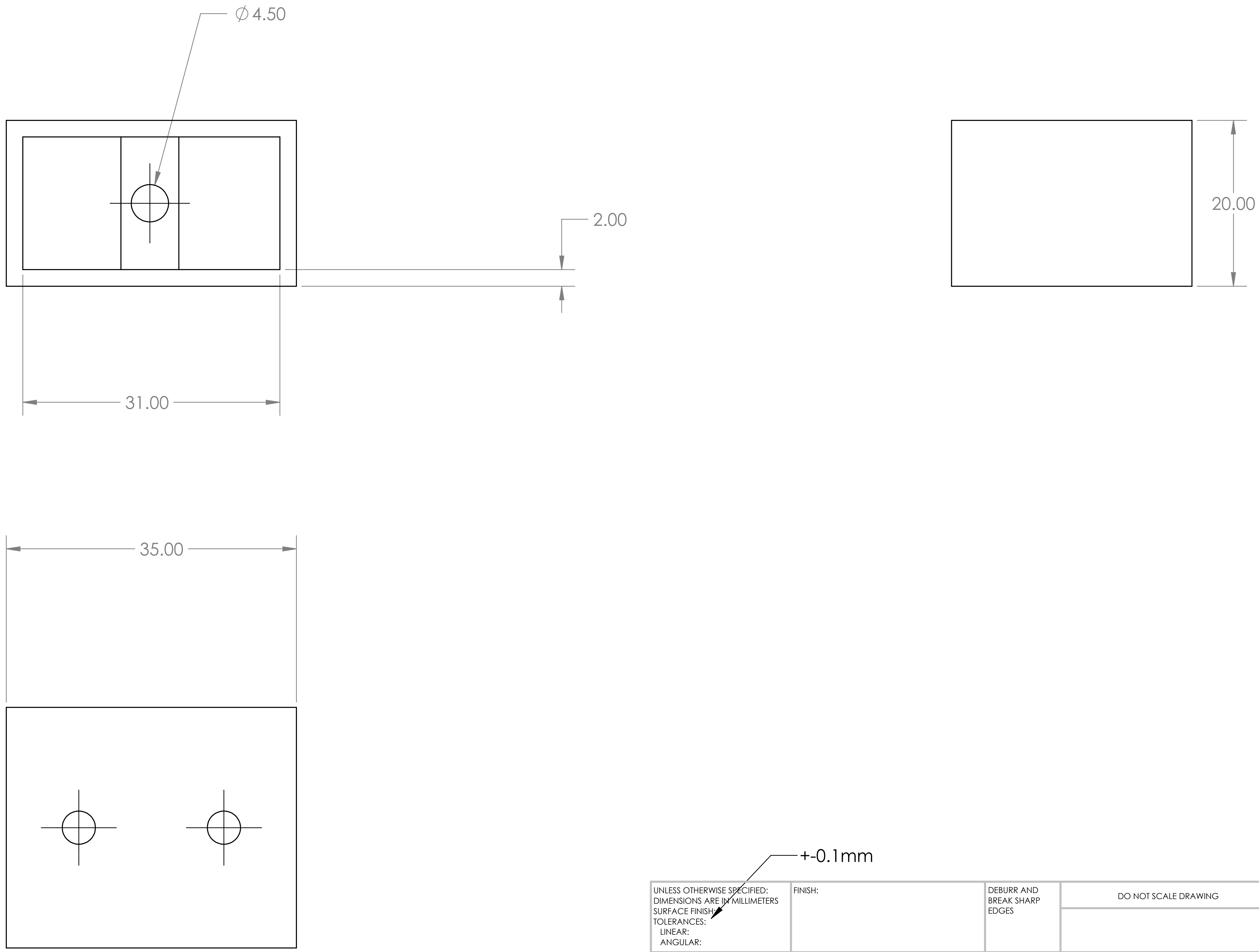
DWG NO. 261-Z2

A3

WEIGHT:

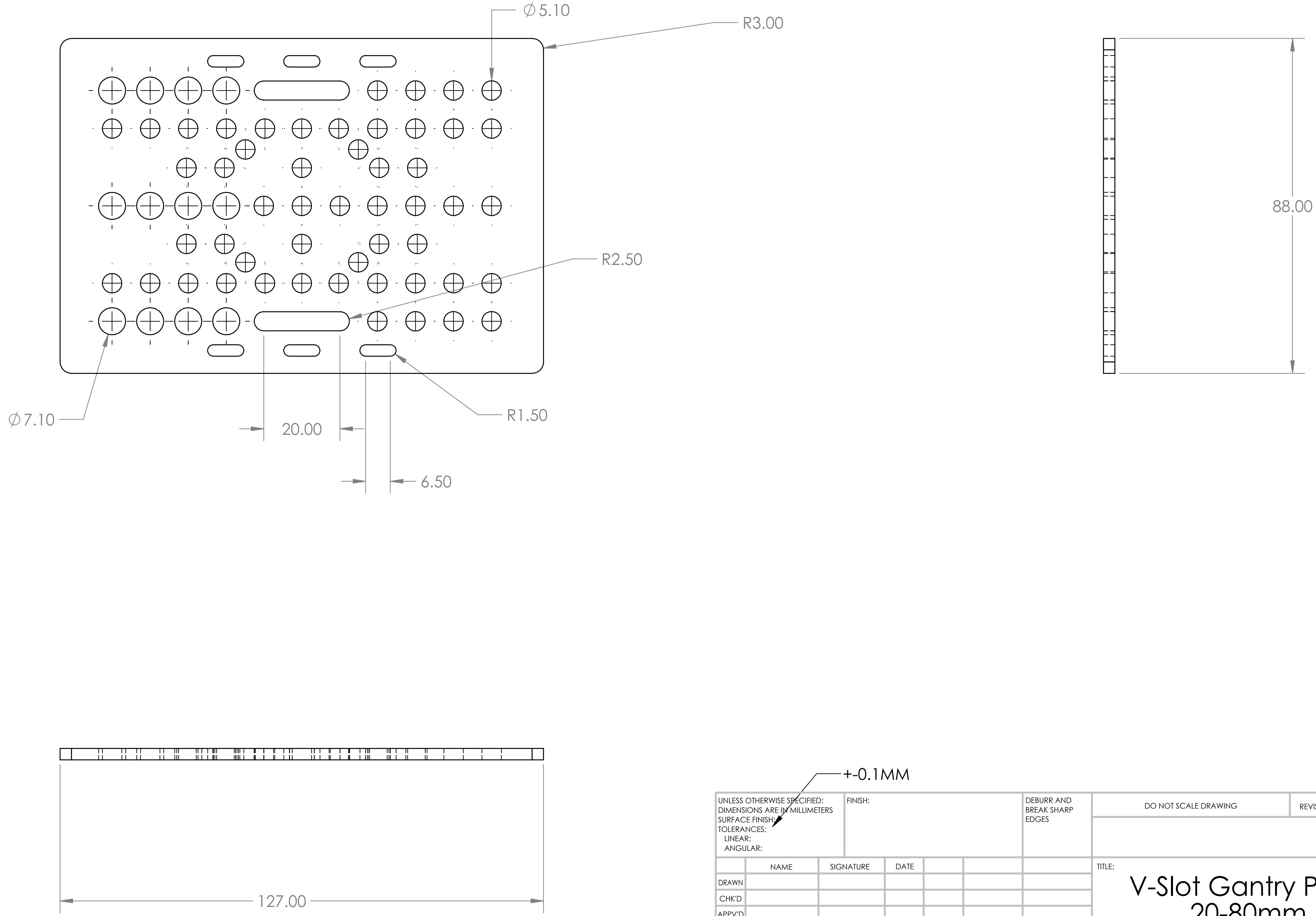
SCALE:1:1

SHEET 1 OF 1



+-0.1mm

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	
	NAME	SIGNATURE	DATE			TITLE: vasi3	
DRAWN							
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL: ABS		DWG NO. 261-Z1	A3
				WEIGHT:		SCALE:2:1	SHEET 1 OF 1



+-0.1MM

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:
V-Slot Gantry Plate 20-80mm

MATERIAL: ABS

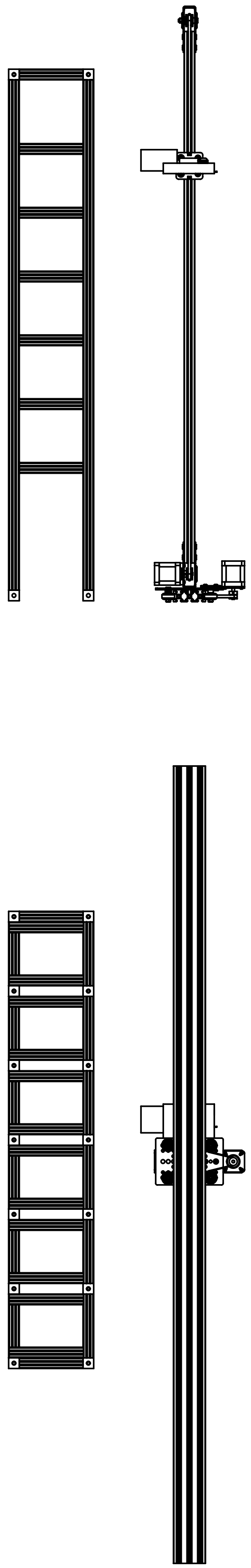
DWG NO. 261-19

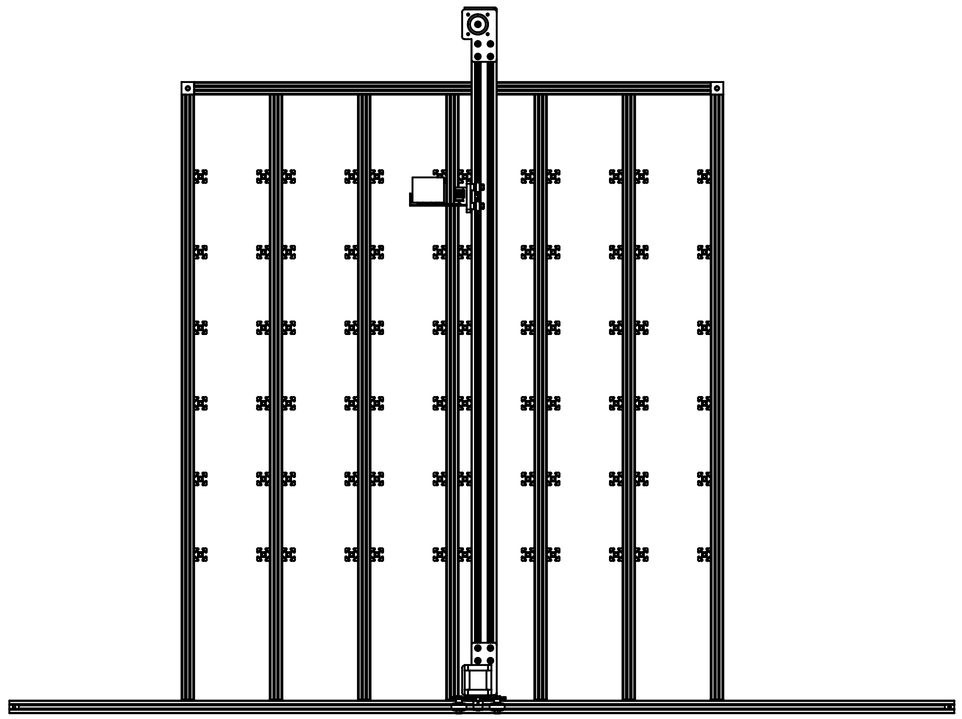
A3

WEIGHT:

SCALE:1:1

SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE		
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A				MATERIAL:	
				WEIGHT:	

TITLE:

ASSEMBLY

DWG NO.		A3
1		
SCALE:1:20	SHEET 1 OF 1	

APPENDIX G: DATA SHEETS

SIEMENS

Data sheet — 6ED1052-1MD08-0BA0

LOGO! 12/24RCE, logic module, disp PS/I/O: 12/24VDC/relay, 8 DI (4AI)/4DO, memory 400 blocks, modular expandable, Ethernet, integr. web server, data log, user-defined Web pages, standard microSD card for LOGO! Soft Comfort V8 or higher, older projects executable

Figure similar

Display	
with display	Yes
Installation type/mounting	
Mounting	on 35 mm DIN rail, 4 spacing units wide
Supply voltage	
Rated value (DC)	
• 12 V DC	Yes
• 24 V DC	Yes
permissible range, lower limit (DC)	10.8 V
permissible range, upper limit (DC)	28.8 V
Time of day	
Time switching clocks	
• Number	400; Max. 400, function-specific
• Power reserve	480 h
Digital inputs	
Number of digital inputs	8; Of which 4 can be used in analog mode (0 to 10 V)

Digital outputs	
Number of digital outputs	4; Relays
Short-circuit protection	No; external fusing necessary
Output current	
• for signal "1" permissible range for 0 to 55 °C, max.	10 A
Relay outputs	
Switching capacity of contacts	
— with inductive load, max.	3 A
— with resistive load, max.	10 A

EMC	
Emission of radio interference acc. to EN 55 011	
• Limit class B, for use in residential areas	Yes

Standards, approvals, certificates	
CE mark	Yes
CSA approval	Yes
UL approval	Yes
FM approval	Yes
developed in accordance with IEC 61131	Yes
according to VDE 0631	Yes
Marine approval	Yes

Ambient conditions	
Ambient temperature during operation	
• min.	-20 °C; No condensation
• max.	55 °C
Ambient temperature during storage/transportation	
• min.	-40 °C
• max.	70 °C

Dimensions	
Width	71.5 mm
Height	90 mm
Depth	60 mm

last modified: 05/13/2020

DRV8825 Stepper Motor Controller IC

1 Features

- PWM Microstepping Stepper Motor Driver
  - Built-In Microstepping Indexer
  - Up to 1/32 Microstepping
- Multiple Decay Modes
  - Mixed Decay
  - Slow Decay
  - Fast Decay
- 8.2-V to 45-V Operating Supply Voltage Range
- 2.5-A Maximum Drive Current at 24 V and T_A = 25°C
- Simple STEP/DIR Interface
- Low Current Sleep Mode
- Built-In 3.3-V Reference Output
- Small Package and Footprint
- Protection Features
  - Overcurrent Protection (OCP)
  - Thermal Shutdown (TSD)
  - VM Undervoltage Lockout (UVLO)
  - Fault Condition Indication Pin (nFAULT)

2 Applications

- Automatic Teller Machines
- Money Handling Machines
- Video Security Cameras
- Printers
- Scanners
- Office Automation Machines
- Gaming Machines
- Factory Automation
- Robotics

3 Description

The DRV8825 provides an integrated motor driver solution for printers, scanners, and other automated equipment applications. The device has two H-bridge drivers and a microstepping indexer, and is intended to drive a bipolar stepper motor. The output driver block consists of N-channel power MOSFET's configured as full H-bridges to drive the motor windings. The DRV8825 is capable of driving up to 2.5 A of current from each output (with proper heat sinking, at 24 V and 25°C).

A simple STEP/DIR interface allows easy interfacing to controller circuits. Mode pins allow for configuration of the motor in full-step up to 1/32-step modes. Decay mode is configurable so that slow decay, fast decay, or mixed decay can be used. A low-power sleep mode is provided which shuts down internal circuitry to achieve very low quiescent current draw. This sleep mode can be set using a dedicated nSLEEP pin.

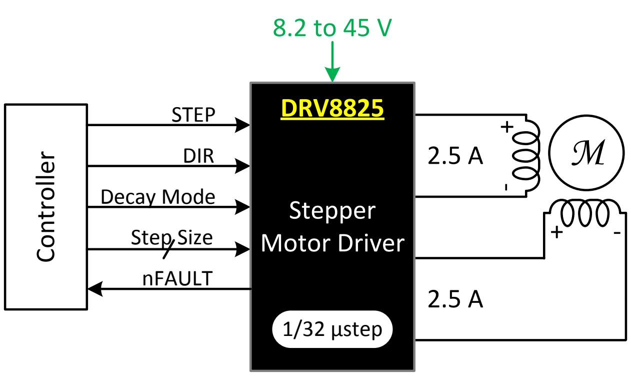
Internal shutdown functions are provided for overcurrent, short circuit, under voltage lockout and over temperature. Fault conditions are indicated via the nFAULT pin.

Device Information(1)

PART NUMBER	PACKAGE	BODY SIZE (NOM)
DRV8825	HTSSOP (28)	9.70 mm × 6.40 mm

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

4 Simplified Schematic



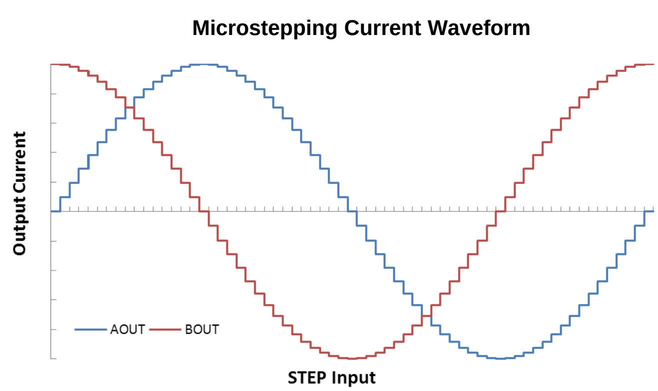
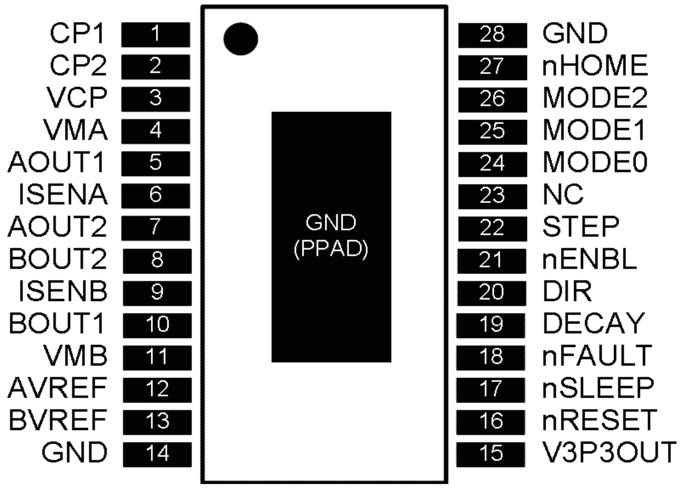


Table of Contents

5 Revision History

Changes from Revision E (August 2013) to Revision F	**Page**
• Added new sections and reordered data sheet to fit new TI flow	1
• Updated pin descriptions	3
• Added power supply ramp rate and updated ISENSEx pin voltage in *Absolute Maximum Ratings*	4
• Updated V_{IL} voltage minimum and typical in *Electrical Characteristics*	6
• Updated I_{IN} and t_{DEG} in *Electrical Characteristics*	6

6 Pin Configuration and Functions



Pin Functions

PIN		I/O (1)	DESCRIPTION	EXTERNAL COMPONENTS OR CONNECTIONS
NAME	NO.			
POWER AND GROUND				
CP1	1	I/O	Charge pump flying capacitor	Connect a 0.01-μF 50-V capacitor between CP1 and CP2.
CP2	2	I/O	Charge pump flying capacitor	
GND	14, 28	—	Device ground	
VCP	3	I/O	High-side gate drive voltage	Connect a 0.1-μF 16-V ceramic capacitor and a 1-MΩ resistor to VM.
VMA	4	—	Bridge A power supply	Connect to motor supply (8.2 to 45 V). Both pins must be connected to the same supply, bypassed with a 0.1-µF capacitor to GND, and connected to appropriate bulk capacitance.
VMB	11	—	Bridge B power supply	
V3P3OUT	15	O	3.3-V regulator output	Bypass to GND with a 0.47-μF 6.3-V ceramic capacitor. Can be used to supply VREF.
CONTROL				
AVREF	12	I	Bridge A current set reference input	Reference voltage for winding current set. Normally AVREF and BVREF are connected to the same voltage. Can be connected to V3P3OUT.
BVREF	13	I	Bridge B current set reference input	
DECAY	19	I	Decay mode	Low = slow decay, open = mixed decay, high = fast decay. Internal pulldown and pullup.
DIR	20	I	Direction input	Level sets the direction of stepping. Internal pulldown.
MODE0	24	I	Microstep mode 0	MODE0 through MODE2 set the step mode - full, 1/2, 1/4, 1/8/ 1/16, or 1/32 step. Internal pulldown.
MODE1	25	I	Microstep mode 1	
MODE2	26	I	Microstep mode 2	
NC	23	—	No connect	Leave this pin unconnected.
nENBL	21	I	Enable input	Logic high to disable device outputs and indexer operation, logic low to enable. Internal pulldown.
nRESET	16	I	Reset input	Active-low reset input initializes the indexer logic and disables the H-bridge outputs. Internal pulldown.
nSLEEP	17	I	Sleep mode input	Logic high to enable device, logic low to enter low-power sleep mode. Internal pulldown.
STEP	22	I	Step input	Rising edge causes the indexer to move one step. Internal pulldown.
STATUS				
nFAULT	18	OD	Fault	Logic low when in fault condition (overtemp, overcurrent)

(1) Directions: I = input, O = output, OD = open-drain output, IO = input/output

Pin Functions (continued)

PIN NAME	PIN NO.	I/O[1]	DESCRIPTION	EXTERNAL COMPONENTS OR CONNECTIONS
nHOME	27	OD	Home position	Logic low when at home state of step table
OUTPUT				
AOUT1	5	O	Bridge A output 1	Connect to bipolar stepper motor winding A. Positive current is AOUT1 → AOUT2
AOUT2	7	O	Bridge A output 2	
BOUT1	10	O	Bridge B output 1	Connect to bipolar stepper motor winding B. Positive current is BOUT1 → BOUT2
BOUT2	8	O	Bridge B output 2	
ISENA	6	I/O	Bridge A ground / Isense	Connect to current sense resistor for bridge A.
ISENB	9	I/O	Bridge B ground / Isense	Connect to current sense resistor for bridge B.

7 Specifications

7.1 Absolute Maximum Ratings[1][2]

		MIN	MAX	UNIT
$V_{(VMx)}$	Power supply voltage	–0.3	47	V
	Power supply ramp rate		1	V/µs
	Digital pin voltage	–0.5	7	V
$V_{(xVREF)}$	Input voltage	–0.3	4	V
	ISENSEx pin voltage[3]	–0.8	0.8	V
	Peak motor drive output current, t < 1 µs		Internally limited	A
	Continuous motor drive output current[4]	0	2.5	A
	Continuous total power dissipation		See *Thermal Information*	
T_J	Operating junction temperature range	–40	150	°C

(1) Stresses beyond those listed under *Absolute Maximum Ratings* may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated under *Recommended Operating Conditions* is not implied. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.
(2) All voltage values are with respect to network ground terminal.
(3) Transients of ±1 V for less than 25 ns are acceptable
(4) Power dissipation and thermal limits must be observed.

7.2 Handling Ratings

			MIN	MAX	UNIT
T_{stg}	Storage temperature range		–60	150	°C
$V_{(ESD)}$	Electrostatic discharge	Human body model (HBM), per ANSI/ESDA/JEDEC JS-001, all pins[1]	–2000	2000	V
		Charged device model (CDM), per JEDEC specification JESD22-C101, all pins[2]	–500	500	

(1) JEDEC document JEP155 states that 500-V HBM allows safe manufacturing with a standard ESD control process.
(2) JEDEC document JEP157 states that 250-V CDM allows safe manufacturing with a standard ESD control process.

7.3 Recommended Operating Conditions

		MIN	NOM	MAX	UNIT
$V_{(VMx)}$	Motor power supply voltage range[1]	8.2		45	V
$V_{(VREF)}$	VREF input voltage[2]	1		3.5	V
I_{V3P3}	V3P3OUT load current	0		1	mA

(1) All V_M pins must be connected to the same supply voltage.
(2) Operational at VREF between 0 to 1 V, but accuracy is degraded.

7.4 Thermal Information

THERMAL METRIC[1]		DRV8825 PWP 28 PINS	UNIT
$R_{\theta JA}$	Junction-to-ambient thermal resistance[2]	31.6	°C/W
$R_{\theta JC(top)}$	Junction-to-case (top) thermal resistance[3]	15.9	
$R_{\theta JB}$	Junction-to-board thermal resistance[4]	5.6	
ψ_{JT}	Junction-to-top characterization parameter[5]	0.2	
ψ_{JB}	Junction-to-board characterization parameter[6]	5.5	
$R_{\theta JC(bot)}$	Junction-to-case (bottom) thermal resistance[7]	1.4	

(1) For more information about traditional and new thermal metrics, see the *IC Package Thermal Metrics* application report, SPRA953.
(2) The junction-to-ambient thermal resistance under natural convection is obtained in a simulation on a JEDEC-standard, high-K board, as specified in JESD51-7, in an environment described in JESD51-2a.
(3) The junction-to-case (top) thermal resistance is obtained by simulating a cold plate test on the package top. No specific JEDEC-standard test exists, but a close description can be found in the ANSI SEMI standard G30-88.
(4) The junction-to-board thermal resistance is obtained by simulating in an environment with a ring cold plate fixture to control the PCB temperature, as described in JESD51-8.
(5) The junction-to-top characterization parameter, ψ_{JT}, estimates the junction temperature of a device in a real system and is extracted from the simulation data for obtaining θ_{JA}, using a procedure described in JESD51-2a (sections 6 and 7).
(6) The junction-to-board characterization parameter, ψ_{JB}, estimates the junction temperature of a device in a real system and is extracted from the simulation data for obtaining θ_{JA} , using a procedure described in JESD51-2a (sections 6 and 7).
(7) The junction-to-case (bottom) thermal resistance is obtained by simulating a cold plate test on the exposed (power) pad. No specific JEDEC standard test exists, but a close description can be found in the ANSI SEMI standard G30-88.

7.5 Electrical Characteristics

over operating free-air temperature range of –40°C to 85°C (unless otherwise noted)

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
POWER SUPPLIES						
I_{VM}	VM operating supply current	$V_{(VMx)}$ = 24 V		5	8	mA
I_{VMQ}	VM sleep mode supply current	$V_{(VMx)}$ = 24 V		10	20	μA
V3P3OUT REGULATOR						
V_{3P3}	V3P3OUT voltage	IOUT = 0 to 1 mA	3.2	3.3	3.4	V
LOGIC-LEVEL INPUTS						
V_{IL}	Input low voltage		0		0.7	V
V_{IH}	Input high voltage		2.2		5.25	V
V_{HYS}	Input hysteresis		0.3	0.45	0.6	V
I_{IL}	Input low current	VIN = 0	–20		20	μA
I_{IH}	Input high current	VIN = 3.3 V			100	μA
R_{PD}	Internal pulldown resistance			100		kΩ
nHOME, nFAULT OUTPUTS (OPEN-DRAIN OUTPUTS)						
V_{OL}	Output low voltage	I_O = 5 mA			0.5	V
I_{OH}	Output high leakage current	V_O = 3.3 V			1	μA
DECAY INPUT						
V_{IL}	Input low threshold voltage	For slow decay mode			0.8	V
V_{IH}	Input high threshold voltage	For fast decay mode	2			V
I_{IN}	Input current		–40		40	μA
R_{PU}	Internal pullup resistance (to 3.3 V)			130		kΩ
R_{PD}	Internal pulldown resistance			80		kΩ
H-BRIDGE FETS						
$R_{DS(ON)}$	HS FET on resistance	$V_{(VMx)}$ = 24 V, I_O = 1 A, T_J = 25°C		0.2		Ω
		$V_{(VMx)}$ = 24 V, I_O = 1 A, T_J = 85°C		0.25	0.32	
	LS FET on resistance	$V_{(VMx)}$ = 24 V, I_O = 1 A, T_J = 25°C		0.2		
		$V_{(VMx)}$ = 24 V, I_O = 1 A, T_J = 85°C		0.25	0.32	
I_{OFF}	Off-state leakage current		–20		20	μA
MOTOR DRIVER						
f_{PWM}	Internal current control PWM frequency			30		kHz
t_{BLANK}	Current sense blanking time			4		μs
t_R	Rise time		30		200	ns
t_F	Fall time		30		200	ns
PROTECTION CIRCUITS						
V_{UVLO}	VM undervoltage lockout voltage	$V_{(VMx)}$ rising		7.8	8.2	V
I_{OCP}	Overcurrent protection trip level		3			A
t_{DEG}	Overcurrent deglitch time			3		μs
t_{TSD}	Thermal shutdown temperature	Die temperature	150	160	180	°C
CURRENT CONTROL						
I_{REF}	xVREF input current	$V_{(xVREF)}$ = 3.3 V	–3		3	μA
V_{TRIP}	xISENSE trip voltage	$V_{(xVREF)}$ = 3.3 V, 100% current setting	635	660	685	mV
ΔI_{TRIP}	Current trip accuracy (relative to programmed value)	$V_{(xVREF)}$ = 3.3 V, 5% current setting	–25%		25%	
		$V_{(xVREF)}$ = 3.3 V, 10% to 34% current setting	–15%		15%	
		$V_{(xVREF)}$ = 3.3 V, 38% to 67% current setting	–10%		10%	
		$V_{(xVREF)}$ = 3.3 V, 71% to 100% current setting	–5%		5%	
A_{ISENSE}	Current sense amplifier gain	Reference only		5		V/V

7.6 Timing Requirements

			MIN	MAX	UNIT
1	f_{STEP}	Step frequency		250	kHz
2	$t_{WH(STEP)}$	Pulse duration, STEP high	1.9		μs
3	$t_{WL(STEP)}$	Pulse duration, STEP low	1.9		μs
4	$t_{SU(STEP)}$	Setup time, command before STEP rising	650		ns
5	$t_{H(STEP)}$	Hold time, command after STEP rising	650		ns
6	t_{ENBL}	Enable time, nENBL active to STEP	650		ns
7	t_{WAKE}	Wakeup time, nSLEEP inactive high to STEP input accepted		1.7	ms

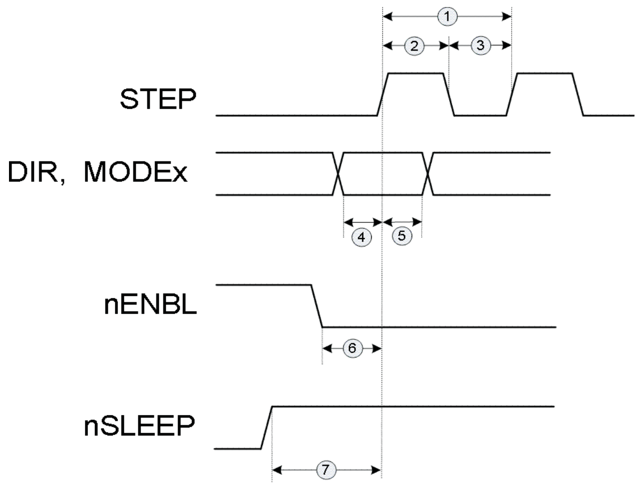


Figure 1. Timing Diagram

7.7 Typical Characteristics

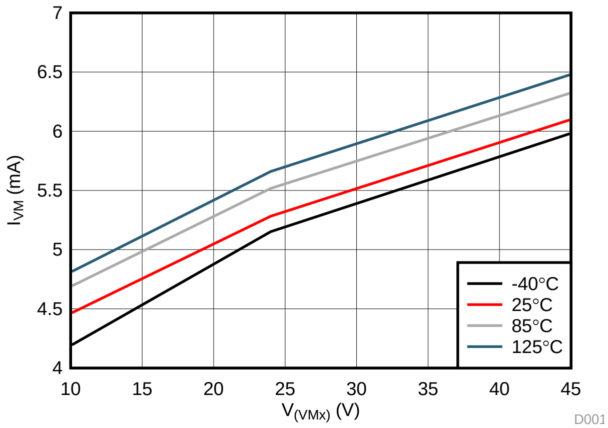


Figure 2. I_{VMx} vs $V_{(VMx)}$

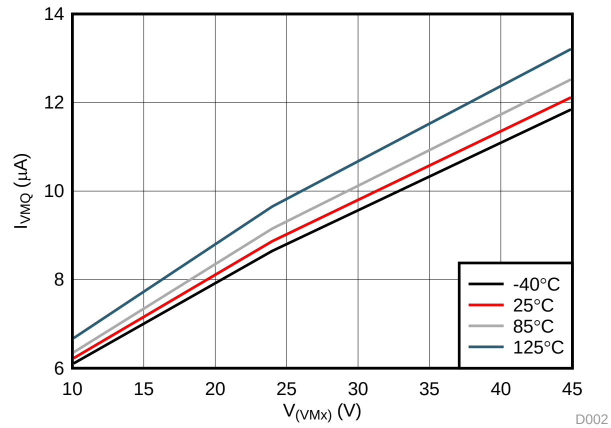


Figure 3. I_{VMxQ} vs $V_{(VMx)}$

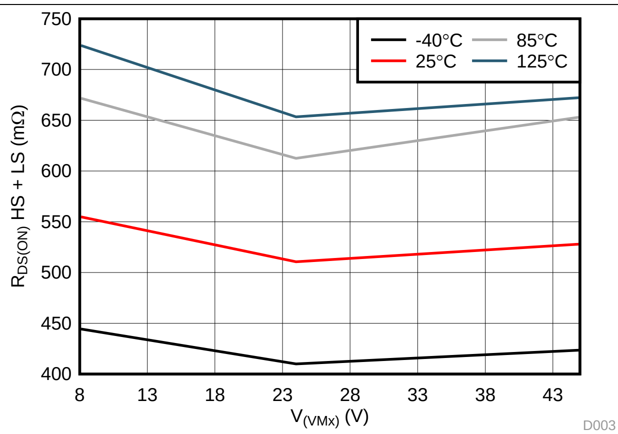


Figure 4. $R_{DS(ON)}$ vs $V_{(VMx)}$

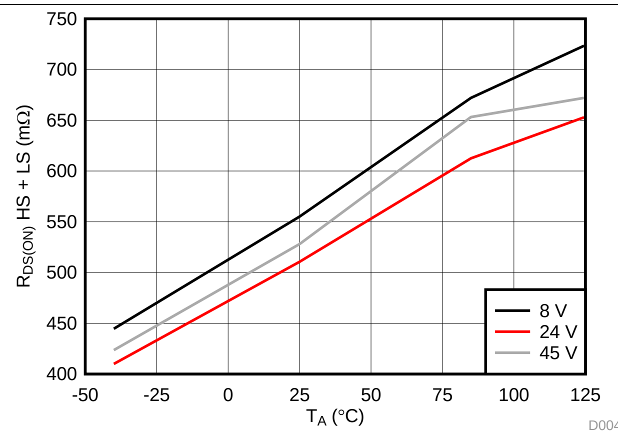


Figure 5. $R_{DS(ON)}$ vs Temperature

8 Detailed Description

8.1 Overview

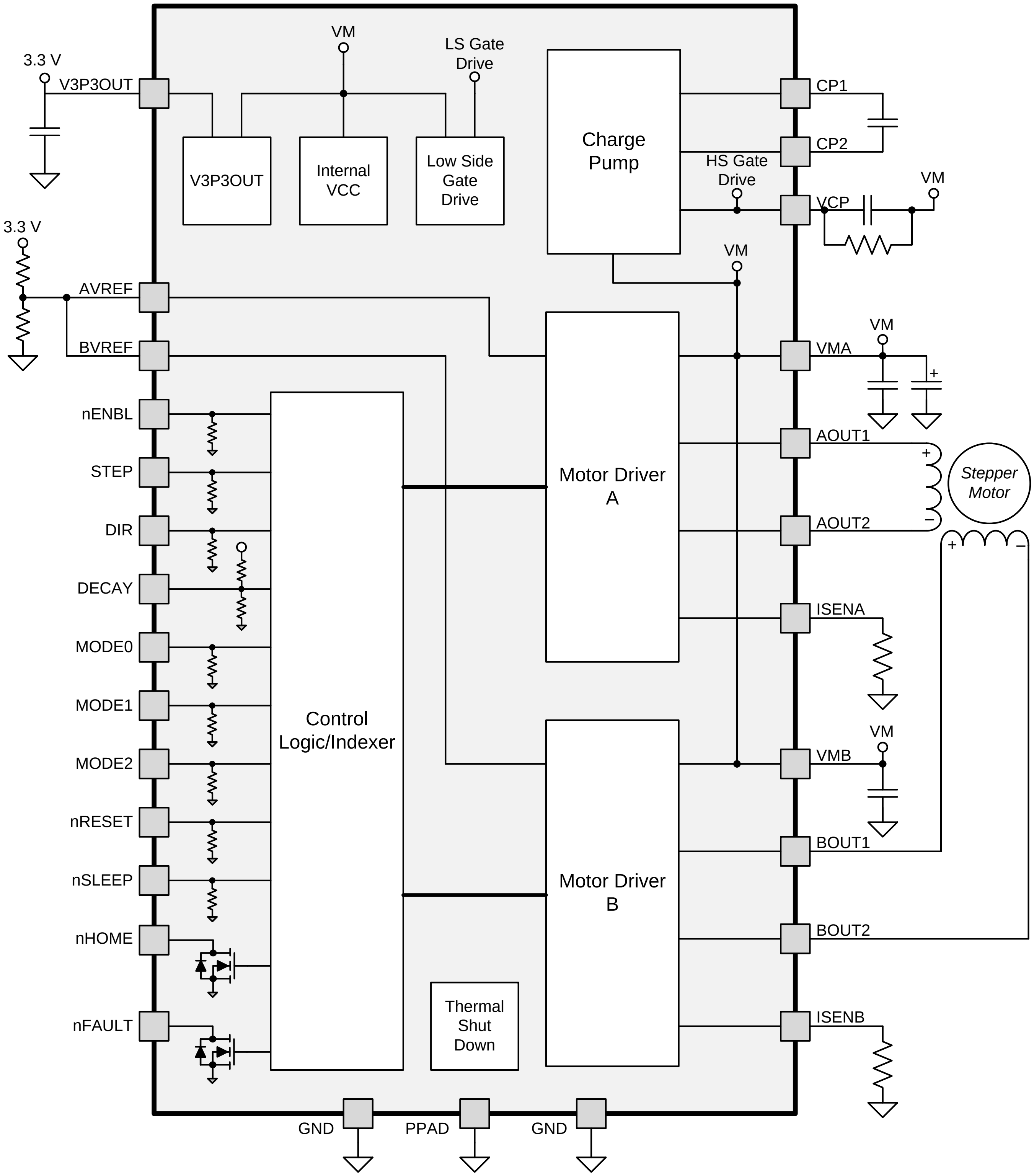
The DRV8825 is an integrated motor driver solution for bipolar stepper motors. The device integrates two NMOS H-bridges, current sense, regulation circuitry, and a microstepping indexer. The DRV8825 can be powered with a supply voltage between 8.2 and 45 V and is capable of providing an output current up to 2.5 A full-scale.

A simple STEP/DIR interface allows for easy interfacing to the controller circuit. The internal indexer is able to execute high-accuracy microstepping without requiring the processor to control the current level.

The current regulation is highly configurable, with three decay modes of operation. Depending on the application requirements, the user can select fast, slow, and mixed decay.

A low-power sleep mode is included which allows the system to save power when not driving the motor.

8.2 Functional Block Diagram



8.3 Feature Description

8.3.1 PWM Motor Drivers

The DRV8825 contains two H-bridge motor drivers with current-control PWM circuitry. Figure 6 shows a block diagram of the motor control circuitry.

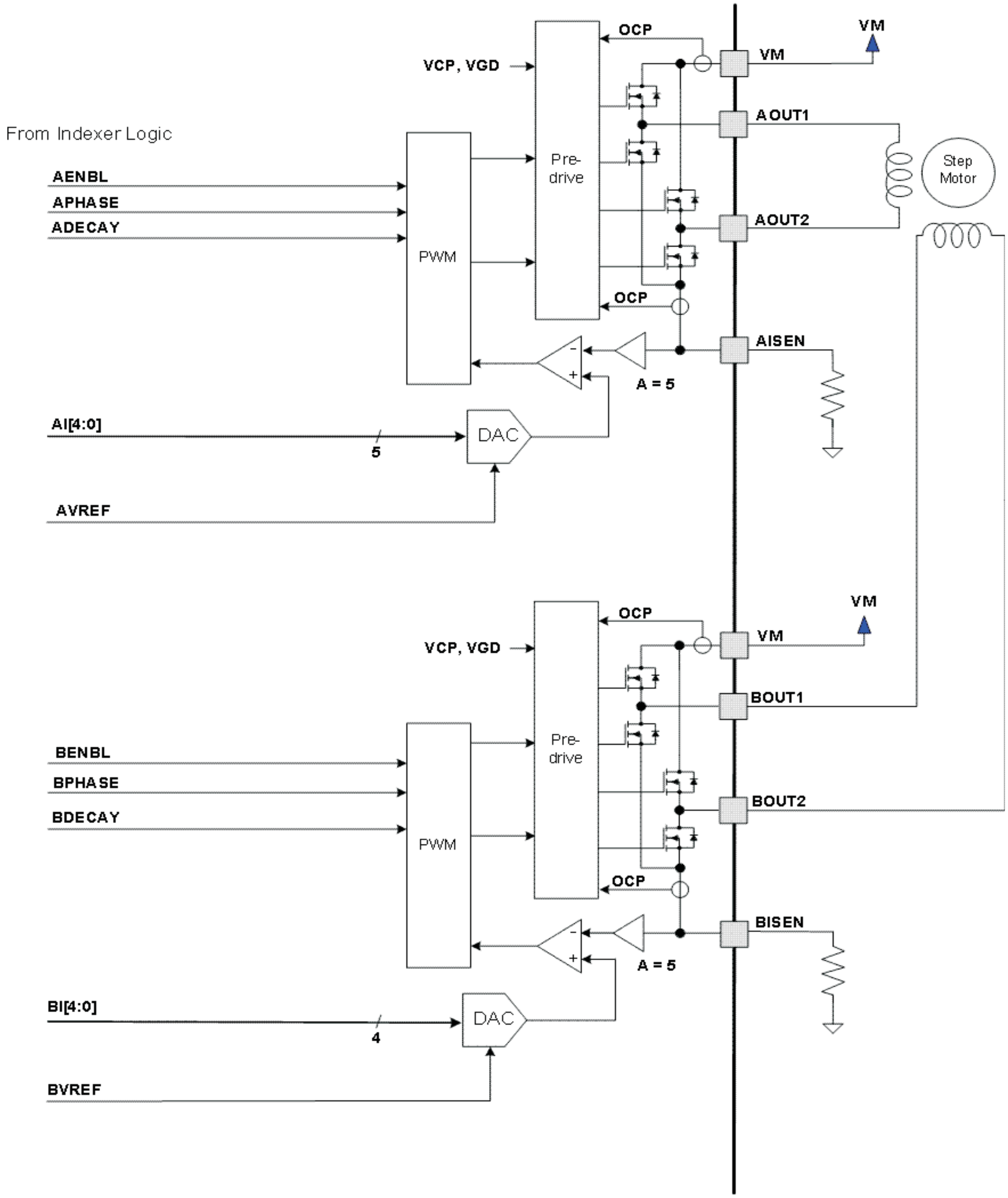


Figure 6. Motor Control Circuitry

Note that there are multiple VM motor power supply pins. All VM pins must be connected together to the motor supply voltage.

Feature Description (continued)

8.3.2 Current Regulation

The current through the motor windings is regulated by a fixed-frequency PWM current regulation, or current chopping. When an H-bridge is enabled, current rises through the winding at a rate dependent on the DC voltage and inductance of the winding. Once the current hits the current chopping threshold, the bridge disables the current until the beginning of the next PWM cycle.

In stepping motors, current regulation is used to vary the current in the two windings in a semi-sinusoidal fashion to provide smooth motion.

The PWM chopping current is set by a comparator which compares the voltage across a current sense resistor connected to the xISEN pins, multiplied by a factor of 5, with a reference voltage. The reference voltage is input from the xVREF pins.

The full-scale (100%) chopping current is calculated in Equation 1.

$$I_{CHOP} = \frac{V_{(xREF)}}{5 \times R_{ISENSE}} \tag{1}$$

Example:

If a 0.25-Ω sense resistor is used and the VREFx pin is 2.5 V, the full-scale (100%) chopping current will be 2.5 V / (5 x 0.25 Ω) = 2 A.

The reference voltage is scaled by an internal DAC that allows fractional stepping of a bipolar stepper motor, as described in the microstepping indexer section below.

8.3.3 Decay Mode

During PWM current chopping, the H-bridge is enabled to drive current through the motor winding until the PWM current chopping threshold is reached. This is shown in Figure 7 as case 1. The current flow direction shown indicates positive current flow.

Once the chopping current threshold is reached, the H-bridge can operate in two different states, fast decay or slow decay.

In fast decay mode, once the PWM chopping current level has been reached, the H-bridge reverses state to allow winding current to flow in a reverse direction. As the winding current approaches 0, the bridge is disabled to prevent any reverse current flow. Fast decay mode is shown in Figure 7 as case 2.

In slow decay mode, winding current is recirculated by enabling both of the low-side FETs in the bridge. This is shown in Figure 7 as case 3.

Feature Description (continued)

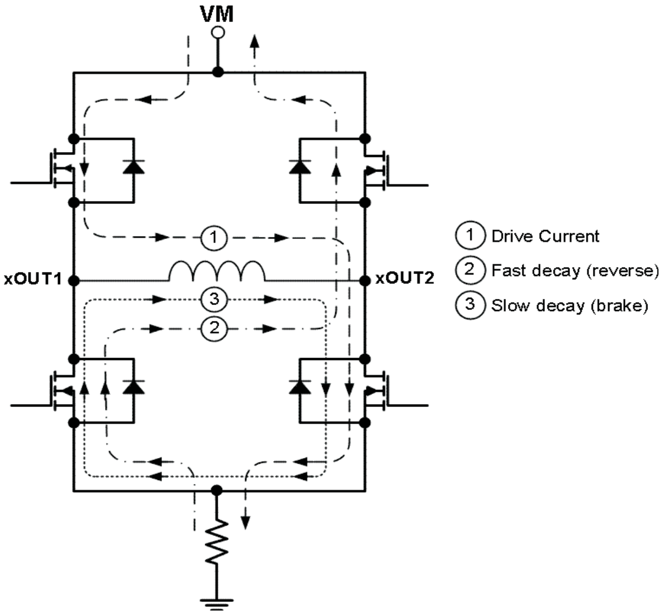


Figure 7. Decay Mode

The DRV8825 supports fast decay, slow decay and a mixed decay mode. Slow, fast, or mixed decay mode is selected by the state of the DECAY pin; logic low selects slow decay, open selects mixed decay operation, and logic high sets fast decay mode. The DECAY pin has both an internal pullup resistor of approximately 130 kΩ and an internal pulldown resistor of approximately 80 kΩ. This sets the mixed decay mode if the pin is left open or undriven.

Mixed decay mode begins as fast decay, but at a fixed period of time (75% of the PWM cycle) switches to slow decay mode for the remainder of the fixed PWM period. This occurs only if the current through the winding is decreasing (per the indexer step table); if the current is increasing, then slow decay is used.

8.3.4 Blanking Time

After the current is enabled in an H-bridge, the voltage on the xISEN pin is ignored for a fixed period of time before enabling the current sense circuitry. This blanking time is fixed at 3.75 μs. Note that the blanking time also sets the minimum on time of the PWM.

8.3.5 Microstepping Indexer

Built-in indexer logic in the DRV8825 allows a number of different stepping configurations. The MODE0 through MODE2 pins are used to configure the stepping format as shown in Table 1.

Table 1. Stepping Format

MODE2	MODE1	MODE0	STEP MODE
0	0	0	Full step (2-phase excitation) with 71% current
0	0	1	1/2 step (1-2 phase excitation)
0	1	0	1/4 step (W1-2 phase excitation)
0	1	1	8 microsteps/step
1	0	0	16 microsteps/step
1	0	1	32 microsteps/step
1	1	0	32 microsteps/step
1	1	1	32 microsteps/step

Table 2 shows the relative current and step directions for different settings of MODEx. At each rising edge of the STEP input, the indexer travels to the next state in the table. The direction is shown with the DIR pin high; if the DIR pin is low the sequence is reversed. Positive current is defined as xOUT1 = positive with respect to xOUT2.

Note that if the step mode is changed while stepping, the indexer will advance to the next valid state for the new MODEx setting at the rising edge of STEP.

The home state is 45°. This state is entered at power-up or application of nRESET. This is shown in Table 2 by the shaded cells. The logic inputs DIR, STEP, nRESET, and MODEx have internal pulldown resistors of 100 kΩ.

Table 2. Relative Current and Step Directions

1/32 STEP	1/16 STEP	1/8 STEP	1/4 STEP	1/2 STEP	FULL STEP 70%	WINDING CURRENT A	WINDING CURRENT B	ELECTRICAL ANGLE
1	1	1	1	1		100%	0%	0
2						100%	5%	3
3	2					100%	10%	6
4						99%	15%	8
5	3	2				98%	20%	11
6						97%	24%	14
7	4					96%	29%	17
8						94%	34%	20
9	5	3	2			92%	38%	23
10						90%	43%	25
11	6					88%	47%	28
12						86%	51%	31
13	7	4				83%	56%	34
14						80%	60%	37
15	8					77%	63%	39
16						74%	67%	42
17	9	5	3	2	1	71%	71%	45
18						67%	74%	48
19	10					63%	77%	51
20						60%	80%	53
21	11	6				56%	83%	56
22						51%	86%	59
23	12					47%	88%	62
24						43%	90%	65
25	13	7	4			38%	92%	68
26						34%	94%	70
27	14					29%	96%	73
28						24%	97%	76
29	15	8				20%	98%	79
30						15%	99%	82
31	16					10%	100%	84
32						5%	100%	87
33	17	9	5	3		0%	100%	90
34						–5%	100%	93
35	18					–10%	100%	96
36						–15%	99%	98
37	19	10				–20%	98%	101
38						–24%	97%	104
39	20					–29%	96%	107

Table 2. Relative Current and Step Directions (continued)

1/32 STEP	1/16 STEP	1/8 STEP	1/4 STEP	1/2 STEP	FULL STEP 70%	WINDING CURRENT A	WINDING CURRENT B	ELECTRICAL ANGLE
40						–34%	94%	110
41	21	11	6			–38%	92%	113
42						–43%	90%	115
43	22					–47%	88%	118
44						–51%	86%	121
45	23	12				–56%	83%	124
46						–60%	80%	127
47	24					–63%	77%	129
48						–67%	74%	132
49	25	13	7	4	2	–71%	71%	135
50						–74%	67%	138
51	26					–77%	63%	141
52						–80%	60%	143
53	27	14				–83%	56%	146
54						–86%	51%	149
55	28					–88%	47%	152
56						–90%	43%	155
57	29	15	8			–92%	38%	158
58						–94%	34%	160
59	30					–96%	29%	163
60						–97%	24%	166
61	31	16				–98%	20%	169
62						–99%	15%	172
63	32					–100%	10%	174
64						–100%	5%	177
65	33	17	9	5		–100%	0%	180
66						–100%	–5%	183
67	34					–100%	–10%	186
68						–99%	–15%	188
69	35	18				–98%	–20%	191
70						–97%	–24%	194
71	36					–96%	–29%	197
72						–94%	–34%	200
73	37	19	10			–92%	–38%	203
74						–90%	–43%	205
75	38					–88%	–47%	208
76						–86%	–51%	211
77	39	20				–83%	–56%	214
78						–80%	–60%	217
79	40					–77%	–63%	219
80						–74%	–67%	222
81	41	21	11	6	3	–71%	–71%	225
82						–67%	–74%	228
83	42					–63%	–77%	231
84						–60%	–80%	233
85	43	22				–56%	–83%	236
86						–51%	–86%	239

Table 2. Relative Current and Step Directions (continued)

1/32 STEP	1/16 STEP	1/8 STEP	1/4 STEP	1/2 STEP	FULL STEP 70%	WINDING CURRENT A	WINDING CURRENT B	ELECTRICAL ANGLE
87	44					–47%	–88%	242
88						–43%	–90%	245
89	45	23	12			–38%	–92%	248
90						–34%	–94%	250
91	46					–29%	–96%	253
92						–24%	–97%	256
93	47	24				–20%	–98%	259
94						–15%	–99%	262
95	48					–10%	–100%	264
96						–5%	–100%	267
97	49	25	13	7		0%	–100%	270
98						5%	–100%	273
99	50					10%	–100%	276
100						15%	–99%	278
101	51	26				20%	–98%	281
102						24%	–97%	284
103	52					29%	–96%	287
104						34%	–94%	290
105	53	27	14			38%	–92%	293
106						43%	–90%	295
107	54					47%	–88%	298
108						51%	–86%	301
109	55	28				56%	–83%	304
110						60%	–80%	307
111	56					63%	–77%	309
112						67%	–74%	312
113	57	29	15	8	4	71%	–71%	315
114						74%	–67%	318
115	58					77%	–63%	321
116						80%	–60%	323
117	59	30				83%	–56%	326
118						86%	–51%	329
119	60					88%	–47%	332
120						90%	–43%	335
121	61	31	16			92%	–38%	338
122						94%	–34%	340
123	62					96%	–29%	343
124						97%	–24%	346
125	63	32				98%	–20%	349
126						99%	–15%	352
127	64					100%	–10%	354
128						100%	–5%	357

8.3.6 nRESET, nENBL, and nSLEEP Operation

The nRESET pin, when driven active low, resets internal logic, and resets the step table to the home position. It also disables the H-bridge drivers. The STEP input is ignored while nRESET is active.

The nENBL pin is used to control the output drivers and enable/disable operation of the indexer. When nENBL is low, the output H-bridges are enabled, and rising edges on the STEP pin are recognized. When nENBL is high, the H-bridges are disabled, the outputs are in a high-impedance state, and the STEP input is ignored.

Driving nSLEEP low will put the device into a low power sleep state. In this state, the H-bridges are disabled, the gate drive charge pump is stopped, the V3P3OUT regulator is disabled, and all internal clocks are stopped. In this state all inputs are ignored until nSLEEP returns inactive high. When returning from sleep mode, some time (approximately 1 ms) needs to pass before applying a STEP input, to allow the internal circuitry to stabilize. Note that nRESET and nENABL have internal pulldown resistors of approximately 100 kΩ. The nSLEEP pin has an internal pulldown resistor of 1 MΩ. nSLEEP and nRESET signals need to be driven to logic high for device operation.

8.3.7 Protection Circuits

The DRV8825 is fully protected against undervoltage, overcurrent, and overtemperature events.

8.3.7.1 Overcurrent Protection (OCP)

An analog current limit circuit on each FET limits the current through the FET by removing the gate drive. If this analog current limit persists for longer than the OCP time, all FETs in the H-bridge will be disabled and the nFAULT pin will be driven low. The device remains disabled until either nRESET pin is applied, or VM is removed and reapplied.

Overcurrent conditions on both high-side and low-side devices; that is, a short to ground, supply, or across the motor winding all result in an overcurrent shutdown. Note that overcurrent protection does not use the current sense circuitry used for PWM current control, and is independent of the I_{SENSE} resistor value or xVREF voltage.

8.3.7.2 Thermal Shutdown (TSD)

If the die temperature exceeds safe limits, all FETs in the H-bridge will be disabled and the nFAULT pin will be driven low. After the die temperature has fallen to a safe level, operation automatically resumes.

8.3.7.3 Undervoltage Lockout (UVLO)

If at any time the voltage on the VM pins falls below the UVLO threshold voltage, all circuitry in the device will be disabled and internal logic will be reset. Operation will resume when $V_{(VMx)}$ rises above the UVLO threshold.

8.4 Device Functional Modes

8.4.1 STEP/DIR Interface

The STEP/DIR interface provides a simple method for advancing through the indexer table. For each rising edge on the STEP pin, the indexer travels to the next state in the table. The direction it moves in the table is determined by the input to the DIR pin. The signals applied to the STEP and DIR pins should not violate the timing diagram specified in Figure 1.

8.4.2 Microstepping

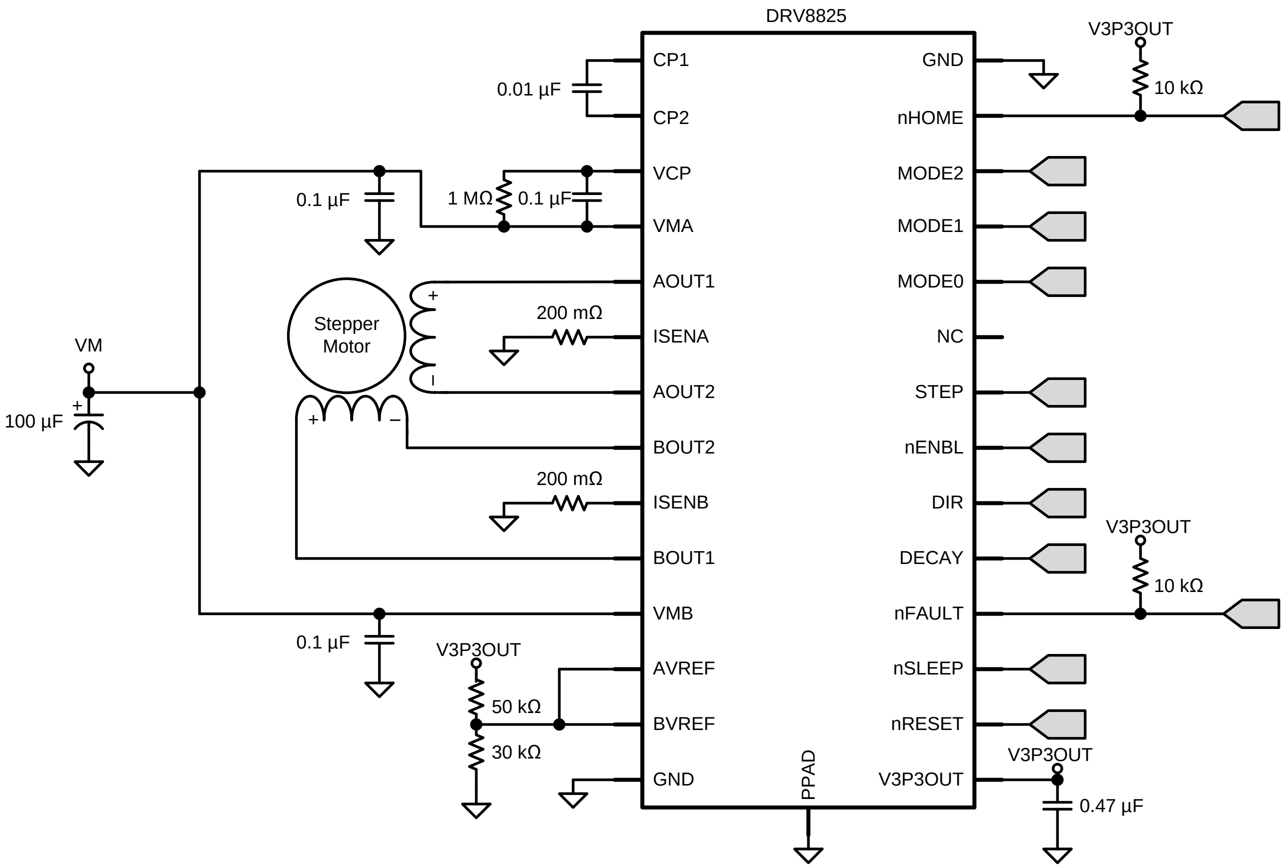
The microstepping indexer allows for a variety of stepping configurations. The state of the indexer is determined by the configuration of the three MODE pins (refer to Table 1 for configuration options). The DRV8825 supports full step up to 1/32 microstepping.

9 Application and Implementation

9.1 Application Information

The DRV8825 is used in bipolar stepper control. The microstepping motor driver provides additional precision and a smooth rotation from the stepper motor. The following design is a common application of the DRV8825.

9.2 Typical Application



9.2.1 Design Requirements

Design Parameter	Reference	Example Value
Supply Voltage	VM	24 V
Motor Winding Resistance	RL	3.9 Ω
Motor Winding Inductance	IL	2.9 mH
Motor Full Step Angle	θstep	1.8°/step
Target Microstepping Level	nm	8 µsteps per step
Target Motor Speed	v	120 rpm
Target Full-Scale Current	IFS	1.25 A

9.2.2 Detailed Design Procedure

9.2.2.1 Stepper Motor Speed

The first step in configuring the DRV8825 requires the desired motor speed and microstepping level. If the target application requires a constant speed, then a square wave with frequency f_{step} must be applied to the STEP pin.

If the target motor startup speed is too high, the motor will not spin. Make sure that the motor can support the target speed or implement an acceleration profile to bring the motor up to speed.

For a desired motor speed (v), microstepping level (n_m), and motor full step angle (θ_{step}),

$$f_{step}\,(\mu steps / second) = \frac{v\left(\frac{rotations}{minute}\right) \times 360\left(\frac{^\circ}{rotation}\right) \times n_m\left(\frac{\mu steps}{step}\right)}{60\left(\frac{seconds}{minute}\right) \times \theta_{step}\left(\frac{^\circ}{step}\right)} \tag{2}$$

$$f_{step}\,(\mu steps / second) = \frac{120\left(\frac{rotations}{minute}\right) \times 360\left(\frac{^\circ}{rotation}\right) \times 8\left(\frac{\mu steps}{step}\right)}{60\left(\frac{seconds}{minute}\right) \times 1.8\left(\frac{^\circ}{step}\right)} \tag{3}$$

θ_{step} can be found in the stepper motor data sheet or written on the motor itself.

For the DRV8825, the microstepping level is set by the MODE pins and can be any of the settings in Table 1. Higher microstepping will mean a smoother motor motion and less audible noise, but will increase switching losses and require a higher f_{step} to achieve the same motor speed.

9.2.2.2 Current Regulation

In a stepper motor, the set full-scale current (I_{FS}) is the maximum current driven through either winding. This quantity depends on the xVREF analog voltage and the sense resistor value (R_{SENSE}). During stepping, I_{FS} defines the current chopping threshold (I_{TRIP}) for the maximum current step. The gain of DRV8825 is set for 5 V/V.

$$I_{FS}\,(A) = \frac{xVREF(V)}{A_v \times R_{SENSE}\,(\Omega)} = \frac{xVREF(V)}{5 \times R_{SENSE}\,(\Omega)} \tag{4}$$

To achieve I_{FS} = 1.25 A with R_{SENSE} of 0.2 Ω, xVREF should be 1.25 V.

9.2.2.3 Decay Modes

The DRV8825 supports three different decay modes: slow decay, fast decay, and mixed decay. The current through the motor windings is regulated using a fixed-frequency PWM scheme. This means that after any drive phase, when a motor winding current has hit the current chopping threshold (I_{TRIP}), the DRV8825 will place the winding in one of the three decay modes until the PWM cycle has expired. Afterward, a new drive phase starts.

The blanking time, t_{BLANK}, defines the minimum drive time for the current chopping. I_{TRIP} is ignored during t_{BLANK}, so the winding current may overshoot the trip level.

9.2.3 Application Curves

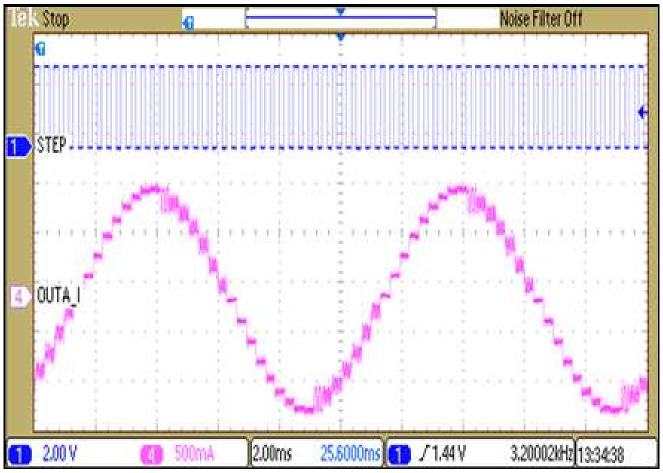


Figure 8. Microstepping Current (Phase A) vs STEP Input, Mixed Decay

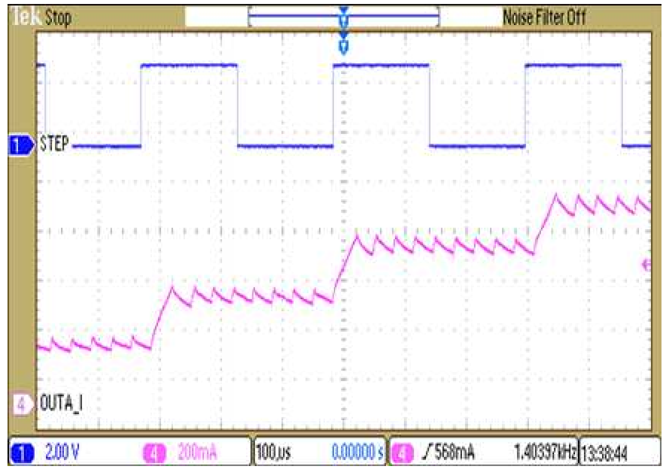


Figure 9. Microstepping Current (Phase A) vs STEP Input, Slow Decay on Increasing Steps

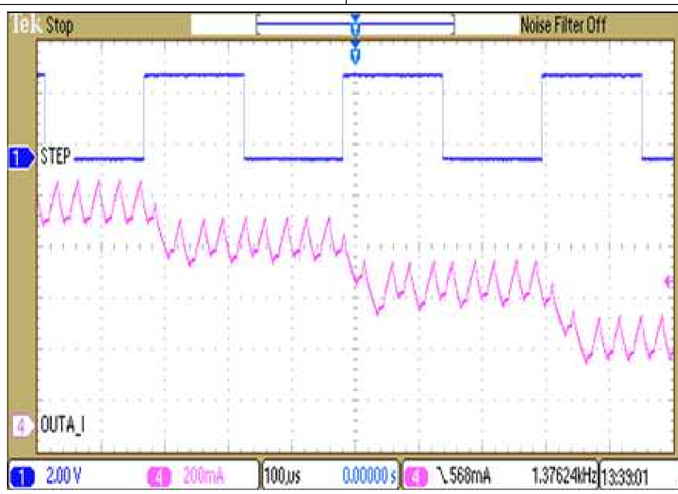


Figure 10. Microstepping Current (Phase A) vs STEP Input, Mixed Decay on Decreasing Steps

10 Power Supply Recommendations

The DRV8825 is designed to operate from an input voltage supply (VMx) range between 8.2 and 45 V. Two 0.1-µF ceramic capacitors rated for VMx must be placed as close as possible to the VMA and VMB pins respectively (one on each pin). In addition to the local decoupling caps, additional bulk capacitance is required and must be sized accordingly to the application requirements.

10.1 Bulk Capacitance

Bulk capacitance sizing is an important factor in motor drive system design. It is dependent on a variety of factors including:

- Type of power supply
- Acceptable supply voltage ripple
- Parasitic inductance in the power supply wiring
- Type of motor (brushed DC, brushless DC, stepper)
- Motor startup current
- Motor braking method

The inductance between the power supply and motor drive system will limit the rate current can change from the power supply. If the local bulk capacitance is too small, the system will respond to excessive current demands or dumps from the motor with a change in voltage. You should size the bulk capacitance to meet acceptable voltage ripple levels.

The data sheet generally provides a recommended value but system level testing is required to determine the appropriate sized bulk capacitor.

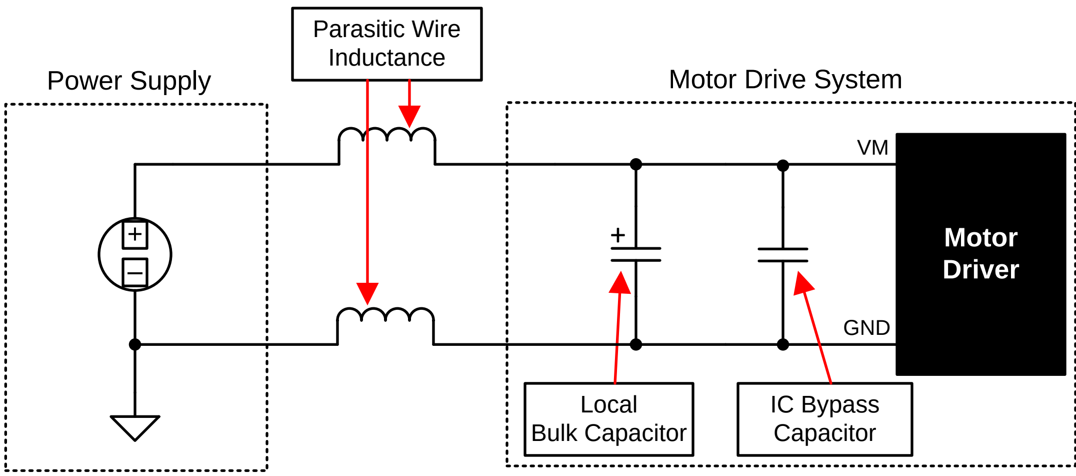


Figure 11. Setup of Motor Drive System With External Power Supply

10.2 Power Supply and Logic Sequencing

There is no specific sequence for powering-up the DRV8825. It is okay for digital input signals to be present before VMx is applied. After VMx is applied to the DRV8825, it begins operation based on the status of the control pins.

11 Layout

11.1 Layout Guidelines

The VMA and VMB pins should be bypassed to GND using low-ESR ceramic bypass capacitors with a recommended value of 0.1-µF rated for VMx. This capacitor should be placed as close to the VMA and VMB pins as possible with a thick trace or ground plane connection to the device GND pin.

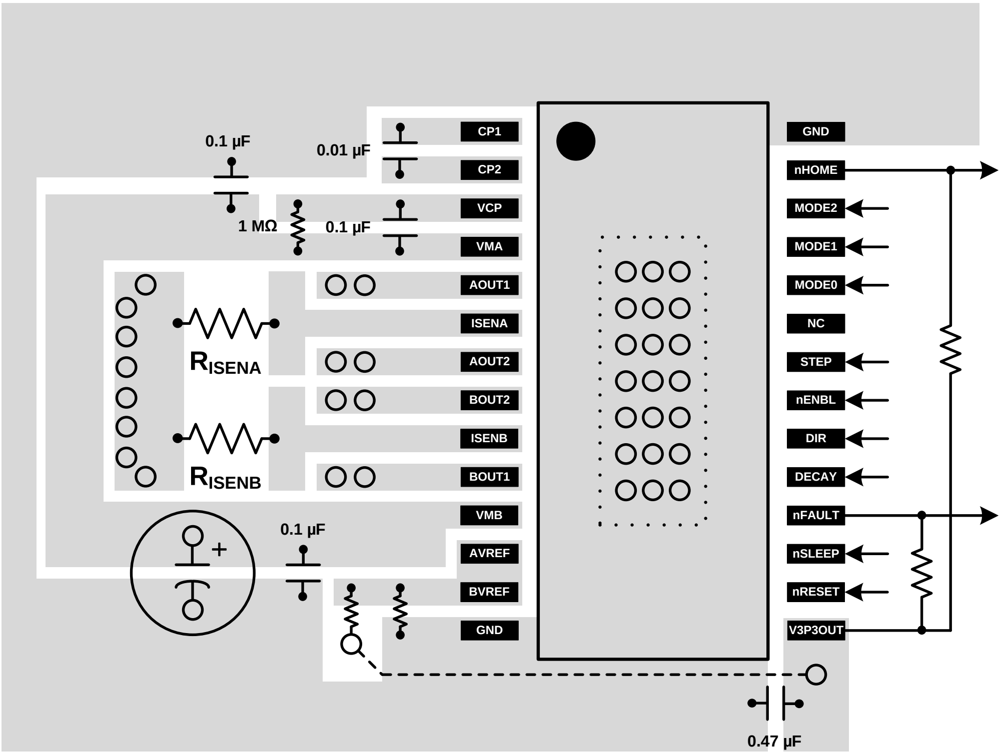
The VMA and VMB pins must be bypassed to ground using an appropriate bulk capacitor. This component may be an electrolytic and should be located close to the DRV8825.

A low-ESR ceramic capacitor must be placed in between the CPL and CPH pins. TI recommends a value of 0.01-µF rated for VMx. Place this component as close to the pins as possible.

A low-ESR ceramic capacitor must be placed in between the VMA and VCP pins. TI recommends a value of 0.1-µF rated for 16 V. Place this component as close to the pins as possible. Also, place a 1-MΩ resistor between VCP and VMA.

Bypass V3P3 to ground with a ceramic capacitor rated 6.3 V. Place this bypass capacitor as close to the pin as possible

11.2 Layout Example



11.3 Thermal Protection

The DRV8825 has thermal shutdown (TSD) as described above. If the die temperature exceeds approximately 150°C, the device will be disabled until the temperature drops to a safe level.

Any tendency of the device to enter TSD is an indication of either excessive power dissipation, insufficient heatsinking, or too high an ambient temperature.

11.3.1 Power Dissipation

Power dissipation in the DRV8825 is dominated by the power dissipated in the output FET resistance, or $R_{DS(ON)}$. Average power dissipation when running a stepper motor can be roughly estimated by Equation 5.

Thermal Protection (continued)

$$P_{TOT} = 4 \times R_{DS(ON)} \times \left(I_{OUT(RMS)}\right)^2 \quad (5)$$

where P_{TOT} is the total power dissipation, $R_{DS(ON)}$ is the resistance of each FET, and $I_{OUT(RMS)}$ is the RMS output current being applied to each winding. $I_{OUT(RMS)}$ is equal to the approximately 0.7x the full-scale output current setting. The factor of 4 comes from the fact that there are two motor windings, and at any instant two FETs are conducting winding current for each winding (one high-side and one low-side).

The maximum amount of power that can be dissipated in the device is dependent on ambient temperature and heatsinking.

Note that $R_{DS(ON)}$ increases with temperature, so as the device heats, the power dissipation increases. This must be taken into consideration when sizing the heatsink.

11.3.2 Heatsinking

The PowerPAD™ package uses an exposed pad to remove heat from the device. For proper operation, this pad must be thermally connected to copper on the PCB to dissipate heat. On a multi-layer PCB with a ground plane, this can be accomplished by adding a number of vias to connect the thermal pad to the ground plane. On PCBs without internal planes, copper area can be added on either side of the PCB to dissipate heat. If the copper area is on the opposite side of the PCB from the device, thermal vias are used to transfer the heat between top and bottom layers.

For details about how to design the PCB, refer to TI application report SLMA002, "PowerPAD™ Thermally Enhanced Package" and TI application brief SLMA004, *PowerPAD™ Made Easy*, available at www.ti.com.

In general, the more copper area that can be provided, the more power can be dissipated. It can be seen that the heatsink effectiveness increases rapidly to about 20 cm^2, then levels off somewhat for larger areas.

12 Device and Documentation Support

12.1 Trademarks

PowerPAD is a trademark of Texas Instruments.

12.2 Electrostatic Discharge Caution

These devices have limited built-in ESD protection. The leads should be shorted together or the device placed in conductive foam during storage or handling to prevent electrostatic damage to the MOS gates.

12.3 Glossary

SLYZ022 — *TI Glossary*.

This glossary lists and explains terms, acronyms, and definitions.

13 Mechanical, Packaging, and Orderable Information

The following pages include mechanical, packaging, and orderable information. This information is the most current data available for the designated devices. This data is subject to change without notice and revision of this document. For browser-based versions of this data sheet, refer to the left-hand navigation.

PACKAGING INFORMATION

Orderable Device	Status (1)	Package Type	Package Drawing	Pins	Package Qty	Eco Plan (2)	Lead/Ball Finish (6)	MSL Peak Temp (3)	Op Temp (°C)	Device Marking (4/5)	Samples
DRV8825PWP	ACTIVE	HTSSOP	PWP	28	50	Green (RoHS & no Sb/Br)	NIPDAU	Level-3-260C-168 HR	-40 to 85	DRV8825	Samples
DRV8825PWPR	ACTIVE	HTSSOP	PWP	28	2000	Green (RoHS & no Sb/Br)	NIPDAU	Level-3-260C-168 HR	-40 to 85	DRV8825	Samples

(1) The marketing status values are defined as follows:
ACTIVE: Product device recommended for new designs.
LIFEBUY: TI has announced that the device will be discontinued, and a lifetime-buy period is in effect.
NRND: Not recommended for new designs. Device is in production to support existing customers, but TI does not recommend using this part in a new design.
PREVIEW: Device has been announced but is not in production. Samples may or may not be available.
OBSOLETE: TI has discontinued the production of the device.

(2) **RoHS:** TI defines "RoHS" to mean semiconductor products that are compliant with the current EU RoHS requirements for all 10 RoHS substances, including the requirement that RoHS substance do not exceed 0.1% by weight in homogeneous materials. Where designed to be soldered at high temperatures, "RoHS" products are suitable for use in specified lead-free processes. TI may reference these types of products as "Pb-Free".
RoHS Exempt: TI defines "RoHS Exempt" to mean products that contain lead but are compliant with EU RoHS pursuant to a specific EU RoHS exemption.
Green: TI defines "Green" to mean the content of Chlorine (Cl) and Bromine (Br) based flame retardants meet JS709B low halogen requirements of <=1000ppm threshold. Antimony trioxide based flame retardants must also meet the <=1000ppm threshold requirement.

(3) MSL, Peak Temp. - The Moisture Sensitivity Level rating according to the JEDEC industry standard classifications, and peak solder temperature.

(4) There may be additional marking, which relates to the logo, the lot trace code information, or the environmental category on the device.

(5) Multiple Device Markings will be inside parentheses. Only one Device Marking contained in parentheses and separated by a "~" will appear on a device. If a line is indented then it is a continuation of the previous line and the two combined represent the entire Device Marking for that device.

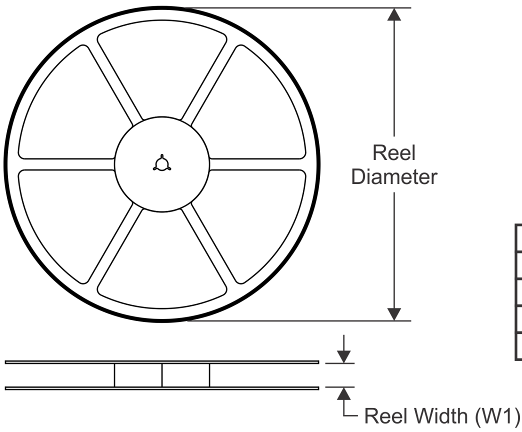
(6) Lead/Ball Finish - Orderable Devices may have multiple material finish options. Finish options are separated by a vertical ruled line. Lead/Ball Finish values may wrap to two lines if the finish value exceeds the maximum column width.

Important Information and Disclaimer: The information provided on this page represents TI's knowledge and belief as of the date that it is provided. TI bases its knowledge and belief on information provided by third parties, and makes no representation or warranty as to the accuracy of such information. Efforts are underway to better integrate information from third parties. TI has taken and continues to take reasonable steps to provide representative and accurate information but may not have conducted destructive testing or chemical analysis on incoming materials and chemicals. TI and TI suppliers consider certain information to be proprietary, and thus CAS numbers and other limited information may not be available for release.

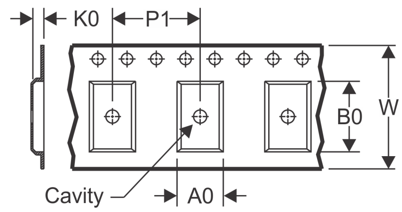
In no event shall TI's liability arising out of such information exceed the total purchase price of the TI part(s) at issue in this document sold by TI to Customer on an annual basis.

TAPE AND REEL INFORMATION

REEL DIMENSIONS

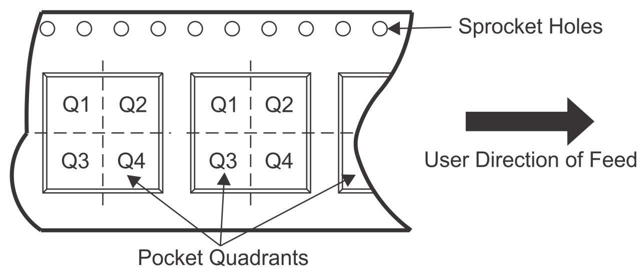


TAPE DIMENSIONS



A0	Dimension designed to accommodate the component width
B0	Dimension designed to accommodate the component length
K0	Dimension designed to accommodate the component thickness
W	Overall width of the carrier tape
P1	Pitch between successive cavity centers

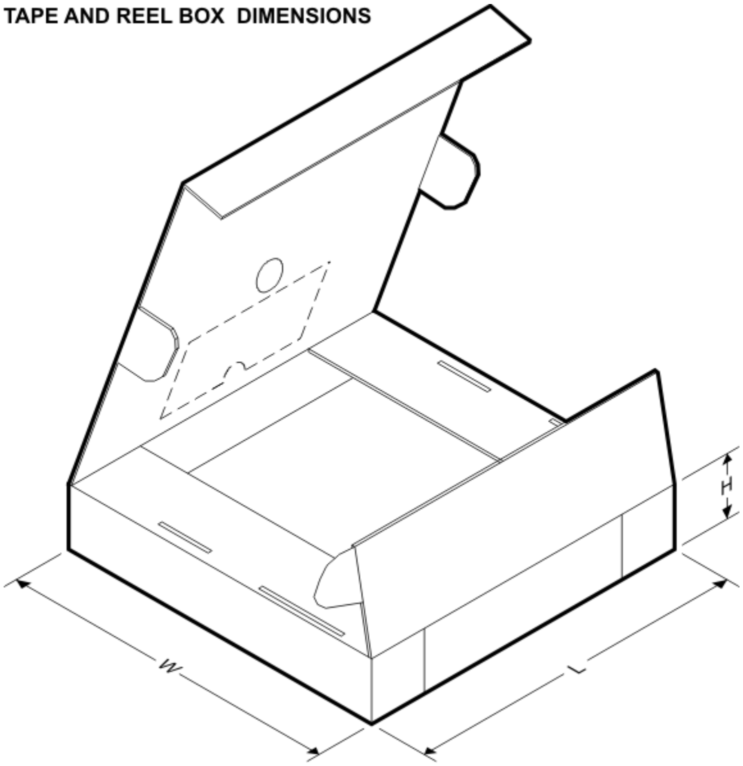
QUADRANT ASSIGNMENTS FOR PIN 1 ORIENTATION IN TAPE



*All dimensions are nominal

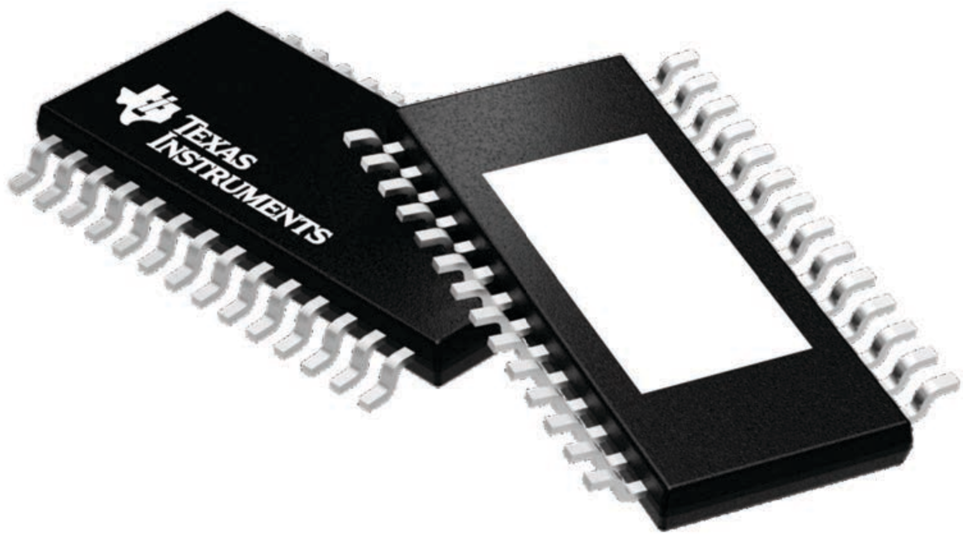
Device	Package Type	Package Drawing	Pins	SPQ	Reel Diameter (mm)	Reel Width W1 (mm)	A0 (mm)	B0 (mm)	K0 (mm)	P1 (mm)	W (mm)	Pin1 Quadrant
DRV8825PWPR	HTSSOP	PWP	28	2000	330.0	16.4	6.9	10.2	1.8	12.0	16.0	Q1

TAPE AND REEL BOX DIMENSIONS



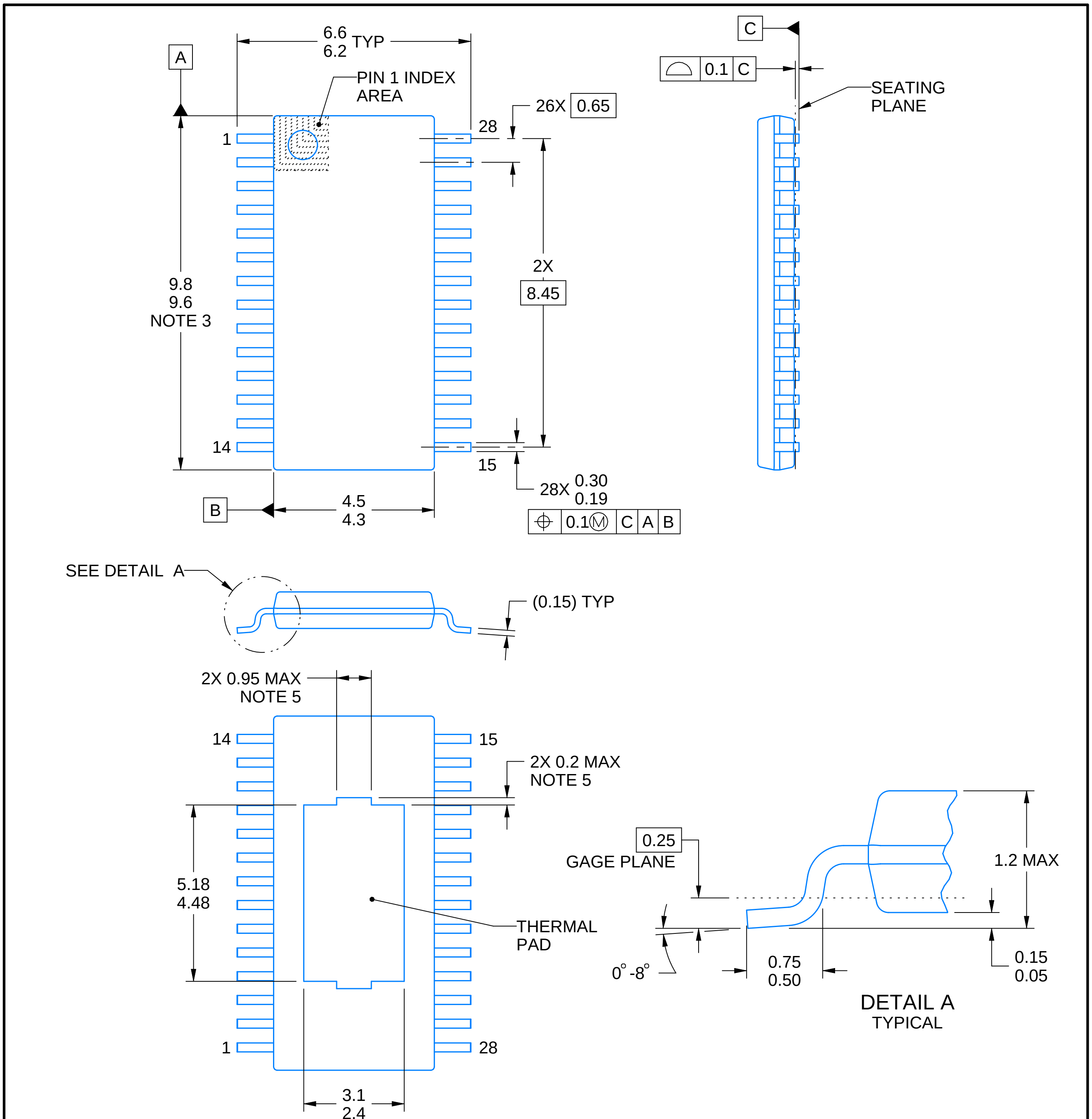
*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Length (mm)	Width (mm)	Height (mm)
DRV8825PWPR	HTSSOP	PWP	28	2000	350.0	350.0	43.0



Images above are just a representation of the package family, actual package may vary.
Refer to the product data sheet for package details.

4224765/A

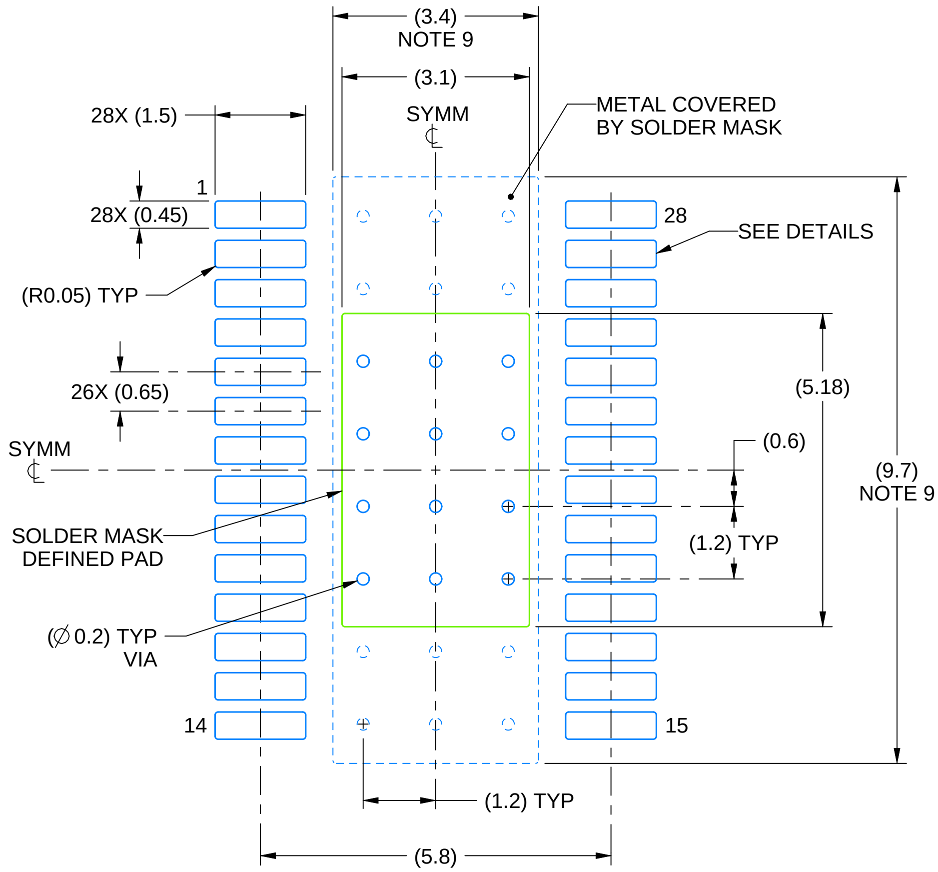


4223582/A 03/2017

PowerPAD is a trademark of Texas Instruments.

NOTES:

1. All linear dimensions are in millimeters. Any dimensions in parenthesis are for reference only. Dimensioning and tolerancing per ASME Y14.5M.
2. This drawing is subject to change without notice.
3. This dimension does not include mold flash, protrusions, or gate burrs. Mold flash, protrusions, or gate burrs shall not exceed 0.15 mm per side.
4. Reference JEDEC registration MO-153.
5. Features may differ or may not be present.



LAND PATTERN EXAMPLE
EXPOSED METAL SHOWN
SCALE: 8X

NON-SOLDER MASK
DEFINED
(PREFERRED)

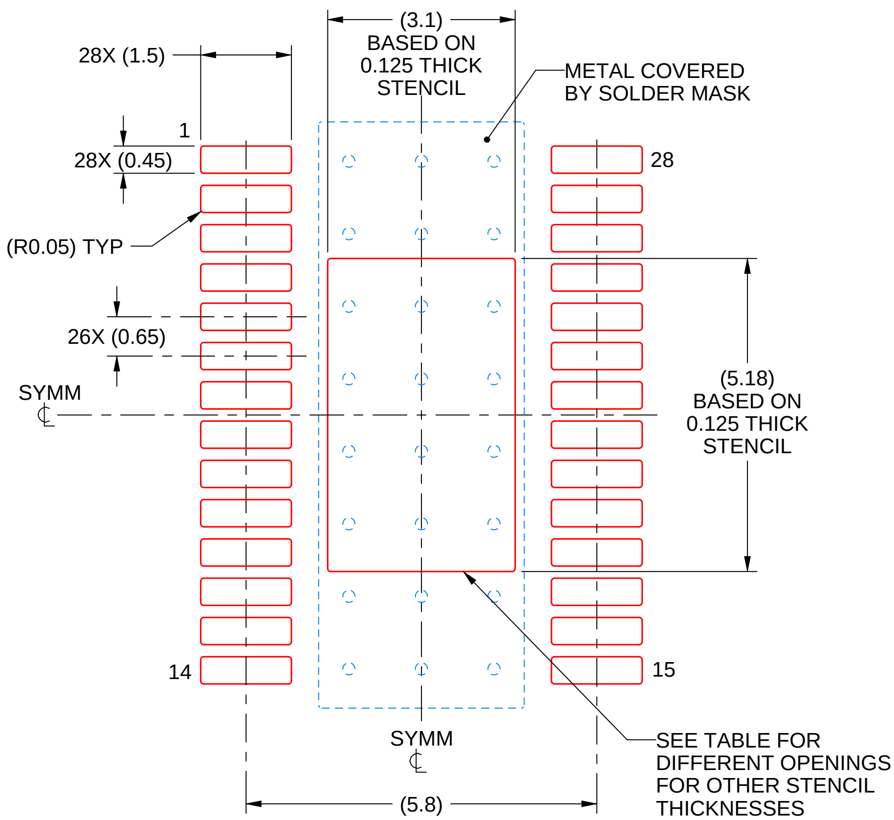
SOLDER MASK
DEFINED

SOLDER MASK DETAILS

4223582/A 03/2017

NOTES: (continued)

6. Publication IPC-7351 may have alternate designs.
7. Solder mask tolerances between and around signal pads can vary based on board fabrication site.
8. This package is designed to be soldered to a thermal pad on the board. For more information, see Texas Instruments literature numbers SLMA002 (www.ti.com/lit/slma002) and SLMA004 (www.ti.com/lit/slma004).
9. Size of metal pad may vary due to creepage requirement.
10. Vias are optional depending on application, refer to device data sheet. It is recommended that vias under paste be filled, plugged or tented.



SOLDER PASTE EXAMPLE
BASED ON 0.125 mm THICK STENCIL
SCALE: 8X

STENCIL THICKNESS	SOLDER STENCIL OPENING
0.1	3.47 X 5.79
0.125	3.10 X 5.18 (SHOWN)
0.15	2.83 X 4.73
0.175	2.62 X 4.38

4223582/A 03/2017

NOTES: (continued)

11. Laser cutting apertures with trapezoidal walls and rounded corners may offer better paste release. IPC-7525 may have alternate design recommendations.
12. Board assembly site may have different recommendations for stencil design.

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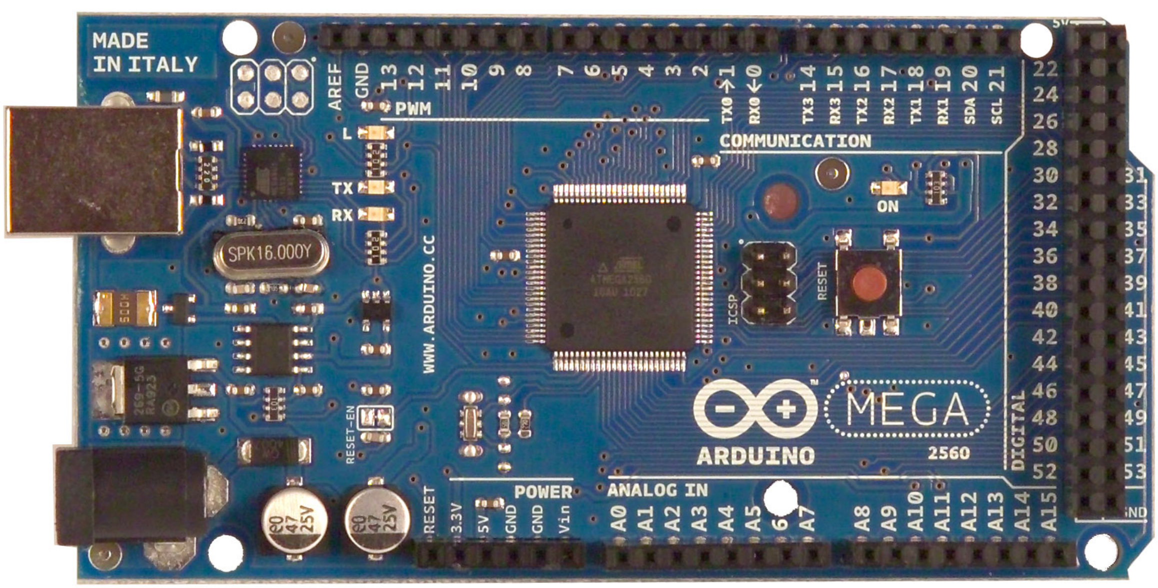
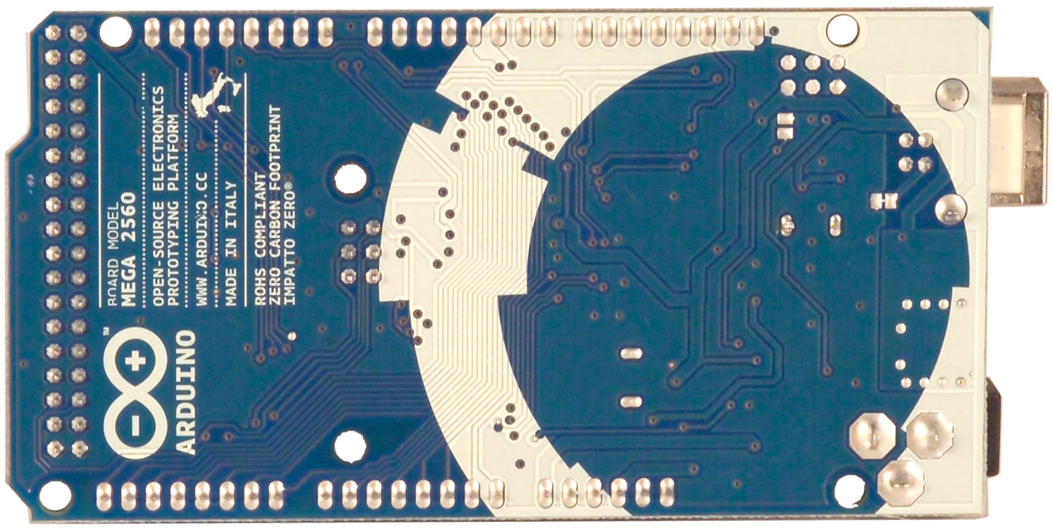
Arduino Mega 2560 Datasheet





Overview

The Arduino Mega 2560 is a microcontroller board based on the ATmega2560 (datasheet). It has 54 digital input/output pins (of which 14 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery to get started. The Mega is compatible with most shields designed for the Arduino Duemilanove or Diecimila.

Schematic & Reference Design

EAGLE files: arduino-mega2560-reference-design.zip

Schematic: arduino-mega2560-schematic.pdf

Summary

Microcontroller	ATmega2560
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	54 (of which 14 provide PWM output)
Analog Input Pins	16
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	256 KB of which 8 KB used by bootloader
SRAM	8 KB
EEPROM	4 KB
Clock Speed	16 MHz

Power

The Arduino Mega can be powered via the USB connection or with an external power supply. The power source is selected automatically.

External (non-USB) power can come either from an AC-to-DC adapter (wall-wart) or battery. The adapter can be connected by plugging a 2.1mm center-positive plug into the board's power jack. Leads from a battery can be inserted in the Gnd and Vin pin headers of the POWER connector.

The board can operate on an external supply of 6 to 20 volts. If supplied with less than 7V, however, the 5V pin may supply less than five volts and the board may be unstable. If using more than 12V, the voltage regulator may overheat and damage the board. The recommended range is 7 to 12 volts.

The Mega2560 differs from all preceding boards in that it does not use the FTDI USB-to-serial driver chip. Instead, it features the Atmega8U2 programmed as a USB-to-serial converter.

The power pins are as follows:

- **VIN.** The input voltage to the Arduino board when it's using an external power source (as opposed to 5 volts from the USB connection or other regulated power source). You can supply voltage through this pin, or, if supplying voltage via the power jack, access it through this pin.
- **5V.** The regulated power supply used to power the microcontroller and other components on the board. This can come either from VIN via an on-board regulator, or be supplied by USB or another regulated 5V supply.
- **3V3.** A 3.3 volt supply generated by the on-board regulator. Maximum current draw is 50 mA.
- **GND.** Ground pins.

Memory

The ATmega2560 has 256 KB of flash memory for storing code (of which 8 KB is used for the bootloader), 8 KB of SRAM and 4 KB of EEPROM (which can be read and written with the EEPROM library).

Input and Output

Each of the 54 digital pins on the Mega can be used as an input or output, using pinMode(), digitalWrite(), and digitalRead() functions. They operate at 5 volts. Each pin can provide or receive a maximum of 40 mA and has an internal pull-up resistor (disconnected by default) of 20-50 kOhms. In addition, some pins have specialized functions:

- **Serial: 0 (RX) and 1 (TX); Serial 1: 19 (RX) and 18 (TX); Serial 2: 17 (RX) and 16 (TX); Serial 3: 15 (RX) and 14 (TX).** Used to receive (RX) and transmit (TX) TTL serial data. Pins 0 and 1 are also connected to the corresponding pins of the ATmega8U2 USB-to-TTL Serial chip.
- **External Interrupts: 2 (interrupt 0), 3 (interrupt 1), 18 (interrupt 5), 19 (interrupt 4), 20 (interrupt 3), and 21 (interrupt 2).** These pins can be configured to trigger an interrupt on a low value, a rising or falling edge, or a change in value. See the attachInterrupt() function for details.
- **PWM: 0 to 13.** Provide 8-bit PWM output with the analogWrite() function.
- **SPI: 50 (MISO), 51 (MOSI), 52 (SCK), 53 (SS).** These pins support SPI communication using the SPI library. The SPI pins are also broken out on the ICSP header, which is physically compatible with the Uno, Duemilanove and Diecimila.
- **LED: 13.** There is a built-in LED connected to digital pin 13. When the pin is HIGH

value, the LED is on, when the pin is LOW, it's off.

- **I^2C: 20 (SDA) and 21 (SCL).** Support I^2C (TWI) communication using the [Wire library] (documentation on the Wiring website). Note that these pins are not in the same location as the I^2C pins on the Duemilanove or Diecimila.

The Mega2560 has 16 analog inputs, each of which provide 10 bits of resolution (i.e. 1024 different values). By default they measure from ground to 5 volts, though is it possible to change the upper end of their range using the AREF pin and analogReference() function.

There are a couple of other pins on the board:

- **AREF.** Reference voltage for the analog inputs. Used with analogReference().
- **Reset.** Bring this line LOW to reset the microcontroller. Typically used to add a reset button to shields which block the one on the board.

Communication

The Arduino Mega2560 has a number of facilities for communicating with a computer, another Arduino, or other microcontrollers. The ATmega2560 provides four hardware UARTs for TTL (5V) serial communication. An ATmega8U2 on the board channels one of these over USB and provides a virtual com port to software on the computer (Windows machines will need a .inf file, but OSX and Linux machines will recognize the board as a COM port automatically. The Arduino software includes a serial monitor which allows simple textual data to be sent to and from the board. The RX and TX LEDs on the board will flash when data is being transmitted via the ATmega8U2 chip and USB connection to the computer (but not for serial communication on pins 0 and 1).
A SoftwareSerial library allows for serial communication on any of the Mega2560's digital pins.
The ATmega2560 also supports I2C (TWI) and SPI communication. The Arduino software includes a Wire library to simplify use of the I2C bus; see the documentation on the Wiring website for details. For SPI communication, use the SPI library.

Programming

The Arduino Mega can be programmed with the Arduino software (download). For details, see the reference and tutorials.
The ATmega2560 on the Arduino Mega comes preburned with a bootloader that allows you to upload new code to it without the use of an external hardware programmer. It

communicates using the original STK500 protocol (reference, C header files).
You can also bypass the bootloader and program the microcontroller through the ICSP (In-Circuit Serial Programming) header; see these instructions for details.

Automatic (Software) Reset

Rather then requiring a physical press of the reset button before an upload, the Arduino Mega2560 is designed in a way that allows it to be reset by software running on a connected computer. One of the hardware flow control lines (DTR) of the ATmega8U2 is connected to the reset line of the ATmega2560 via a 100 nanofarad capacitor. When this line is asserted (taken low), the reset line drops long enough to reset the chip. The Arduino software uses this capability to allow you to upload code by simply pressing the upload button in the Arduino environment. This means that the bootloader can have a shorter timeout, as the lowering of DTR can be well-coordinated with the start of the upload.
This setup has other implications. When the Mega2560 is connected to either a computer running Mac OS X or Linux, it resets each time a connection is made to it from software (via USB). For the following half-second or so, the bootloader is running on the Mega2560. While it is programmed to ignore malformed data (i.e. anything besides an upload of new code), it will intercept the first few bytes of data sent to the board after a connection is opened. If a sketch running on the board receives one-time configuration or other data when it first starts, make sure that the software with which it communicates waits a second after opening the connection and before sending this data.
The Mega2560 contains a trace that can be cut to disable the auto-reset. The pads on either side of the trace can be soldered together to re-enable it. It's labeled "RESET-EN". You may also be able to disable the auto-reset by connecting a 110 ohm resistor from 5V to the reset line; see this forum thread for details.

USB Overcurrent Protection

The Arduino Mega2560 has a resettable polyfuse that protects your computer's USB ports from shorts and overcurrent. Although most computers provide their own internal protection, the fuse provides an extra layer of protection. If more than 500 mA is applied to the USB port, the fuse will automatically break the connection until the short or overload is removed.

Physical Characteristics and Shield Compatibility

The maximum length and width of the Mega2560 PCB are 4 and 2.1 inches respectively, with the USB connector and power jack extending beyond the former dimension. Three screw holes allow the board to be attached to a surface or case. Note that the distance between digital pins 7 and 8 is 160 mil (0.16"), not an even multiple of the 100 mil spacing of the other pins.

The Mega2560 is designed to be compatible with most shields designed for the Uno, Diecimila or Duemilanove. Digital pins 0 to 13 (and the adjacent AREF and GND pins), analog inputs 0 to 5, the power header, and ICSP header are all in equivalent locations. Further the main UART (serial port) is located on the same pins (0 and 1), as are external interrupts 0 and 1 (pins 2 and 3 respectively). SPI is available through the ICSP header on both the Mega2560 and Duemilanove / Diecimila. *Please note that I2C is not located on the same pins on the Mega (20 and 21) as the Duemilanove / Diecimila (analog inputs 4 and 5).*

CUI DEVICES

SERIES: NEMA17-AMT112S | DESCRIPTION: STEPPER SERVO MOTOR

FEATURES

- CUI Devices AMT112S encoder + LIN Engineering stepper motor
- stepper motor with encoder for closed-loop mode when paired with a controller
- small, compact NEMA 17 frame size
- up to 110 oz-in (0.77 N-m) holding torque
- patented capacitive encoder ASIC technology
- incremental resolutions up to 4096 PPR
- resolutions programmable with AMT Viewpoint™ PC software
- digitally set zero position

IN PARTNERSHIP WITH LIN ENGINEERING The Step Motor Specialists BACKED BY MOONS'

MODEL	step angle (°)	current/ phase (A)	resistance/ phase typ (Ω±10%)	inductance /phase typ (mH±20%)	max holding torque (oz-in)	max optimal speed (RPS)	body length max (inch)
NEMA17-13-04SD-AMT112S	1.8	0.67	9.9	12.52	42.0	6	1.34
NEMA17-13-04PD-AMT112S	1.8	1.33	2.5	3.09	42.0	11	1.34
NEMA17-16-06SD-AMT112S	1.8	0.70	10.8	21.84	63.0	3	1.58
NEMA17-16-06PD-AMT112S	1.8	1.40	2.7	5.46	63.0	6	1.58
NEMA17-19-07SD-AMT112S	1.8	1.05	1.3	9.36	83.0	5	1.89
NEMA17-19-07PD-AMT112S	1.8	2.10	5.2	2.34	83.0	9	1.89
NEMA17-23-01D-AMT112S	1.8	2.00	2.0	2.91	110.0	7	2.34

AMT112S ENCODER

ELECTRICAL

parameter	conditions/description	min	typ	max	units
power supply	VDD	4.5	5	5.5	V
start up time			200		ms
current consumption	with unloaded output		16		mA
output high level		VDD-0.1			V
output low level				0.1	V
output current (per channel)				15	mA
rise/fall time			8		ns

INCREMENTAL CHARACTERISTICS

parameter	conditions/description	min	typ	max	units
channels	CMOS Voltage: A, B, Z				
waveform	CMOS voltage square wave				
phase difference	A leads B for CCW rotation (viewed from front)				
quadrature resolutions[1]	48, 96, 100, 125, 192, 200, 250, 256, 360, 384, 400, 500, 512, 768, 800, 1000, 1024, 1600, 2000, 2048, 2500, 4096				PPR
index[2]	one pulse per 360 degree rotation				
accuracy			0.2		degrees
quadrature duty cycle			50		%

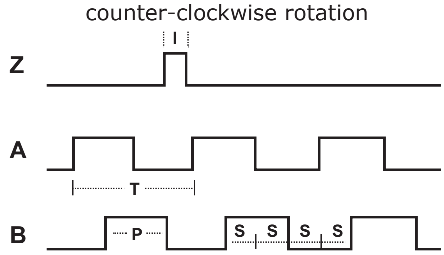
Notes: 1. Resolution programmed with AMT Viewpoint™ PC software. Default resolution set to 400 PPR.
2. Zero position alignment set with AMT One Touch Zero™ module, AMT Viewpoint™ PC software, or serial commands

MECHANICAL

parameter	conditions/description	min	typ	max	units
weight			15.7		g
rotational speed (at each resolution)	48, 96, 100, 125, 192, 200, 250, 256, 384, 400, 500, 512, 800, 1000, 1024, 2048			8000	RPM
	360, 768, 1600, 2000, 4096			4000	RPM
	2500			2500	RPM

ENCODER WAVEFORMS

Figure 1
Quadrature signals with index showing counter-clockwise rotation



The following parameters are defined by the resolution selected for each encoder, where R = resolution.

Parameter	Description	Expression	Units
T	period	360/R	mechanical degrees
P	pulse width	T/2	mechanical degrees
I	index width	P/2	mechanical degrees
S	A/B state width	P/2	mechanical degrees

STEPPER MOTOR SPECIFICATIONS

parameter	conditions/description	min	typ	max	units
motor frame size	NEMA Size 17				
step angle			1.8		°
rated current/phase	see page 1 for details				
rated voltage			24-48		Vdc
resistance/phase	see page 1 for details				
inductance/phase	see page 1 for details				
connection type	bipolar				
rotor inertia	NEMA17-13-04SD-AMT112S, NEMA17-13-04PD-AMT112S NEMA17-16-06SD-AMT112S, NEMA17-16-06PD-AMT112S NEMA17-19-07SD-AMT112S, NEMA17-19-07PD-AMT112S NEMA17-23-01D-AMT112S		0.18 0.28 0.37 0.56		$oz\text{-}in^2$ $oz\text{-}in^2$ $oz\text{-}in^2$ $oz\text{-}in^2$
max holding torque	see page 1 for details				
bearing type	ABEC3				
front shaft OD			5		mm
front shaft length			0.94		inch
max optimal speed	see page 1 for details				
max axial load				6	lb
radial play	at 1 lb load			0.001	inch
end play	at 2 lbs load			0.003	inch
shaft run out			0.002		inch TIR
dielectric strength			500		V
EMI/EMC	EN 55014-1:2007				

SWITCHING SEQUENCE

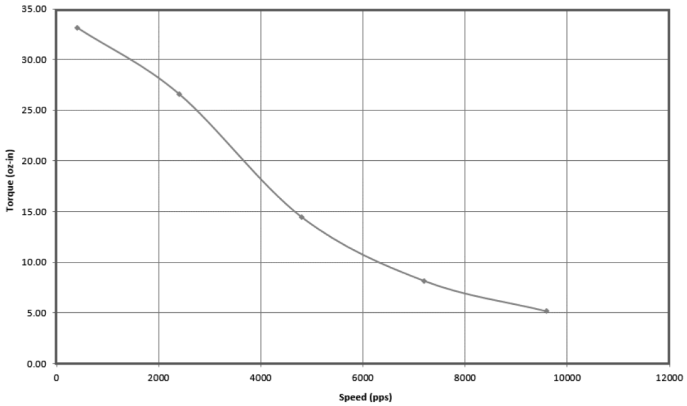
SWITCHING SEQUENCE					
CCW	STEP	A	A	B	B
↓	1	+	-	+	-
	2	+	-	-	+
	3	-	+	-	+
	4	-	+	+	-
	1	+	-	+	-
Motor Rotation Viewed from Front Shaft End					

ENVIRONMENTAL

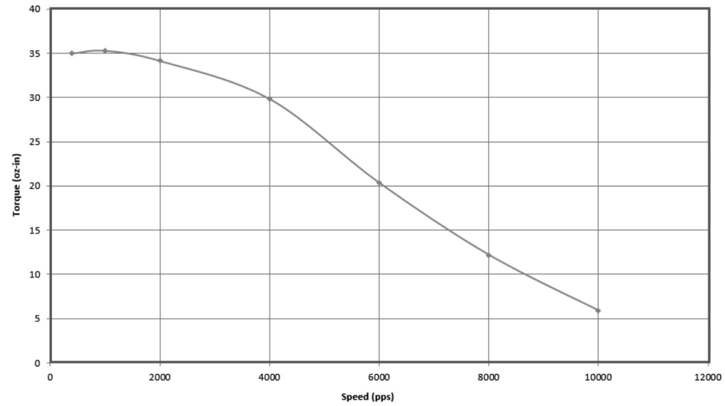
parameter	conditions/description	min	typ	max	units
operating temperature		-20		50	°C
storage temperature		-20		100	°C
humidity	non-condensing			85	%
vibration	10~500 Hz, 5 minute sweep, 2 hours on each XYZ			5	G
shock	3 pulses, 6 ms, 3 on each XYZ			200	G
RoHS	yes				

TORQUE CURVES

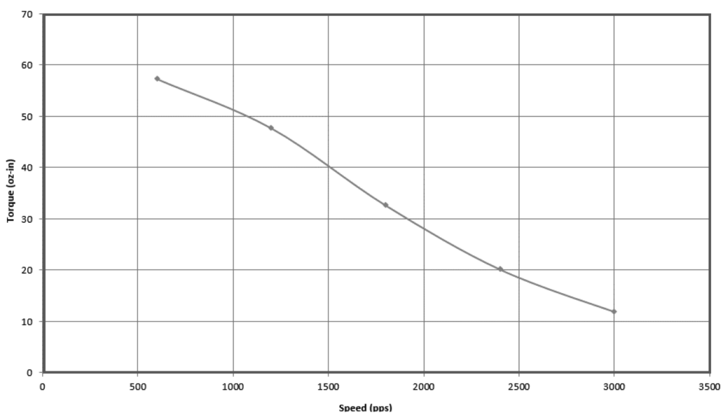
CUI Devices P/N NEMA17-13-04SD-AMT112S
Lin Engineering P/N WO-4118S-04S (1.8 Step Motor)
24 Vdc, 0.67 Amp/Phase, IB463, 1/2 Stepping



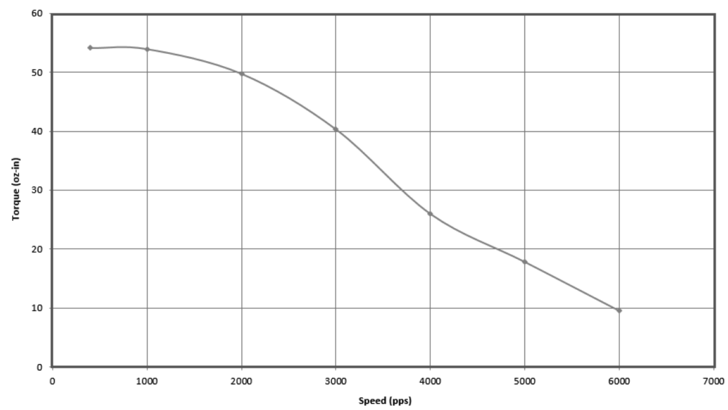
CUI Devices P/N NEMA17-13-04PD-AMT112S
Lin Engineering P/N WO-4118S-04P (1.8 Step Motor)
24 Vdc, 1.33 Amp/Phase, IB462, 1/2 Stepping



CUI Devices P/N NEMA17-16-06SD-AMT112S
Lin Engineering P/N WO-4118M-06S (1.8 Step Motor)
24 Vdc, 0.7 Amp/Phase, R208, 1/2 Stepping

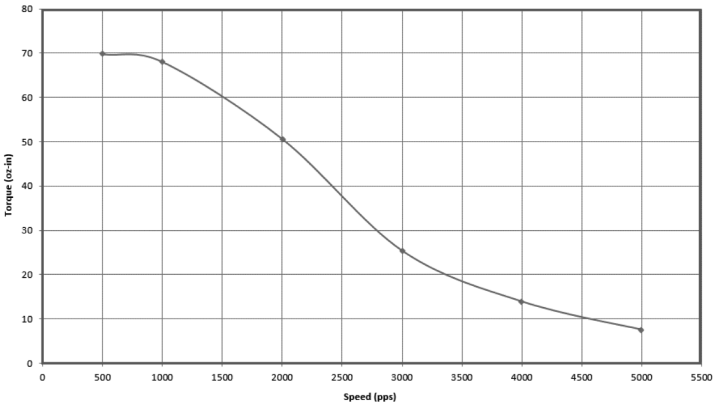


CUI Devices P/N NEMA17-16-06PD-AMT112S
Lin Engineering P/N WO-4118M-06P (1.8 Step Motor)
24 Vdc, 1.4 Amp/Phase, IB462, 1/2 Stepping

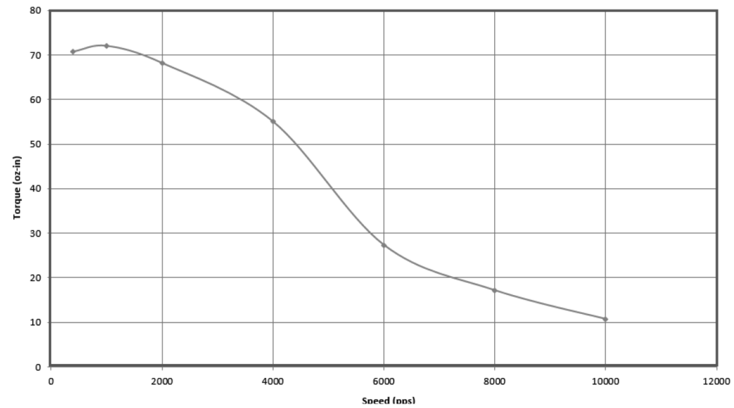


TORQUE CURVES (CONTINUED)

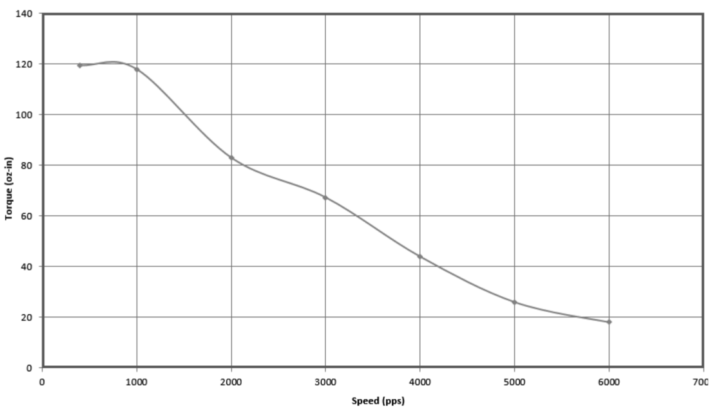
CUI Devices P/N NEMA17-19-07SD-AMT112S
Lin Engineering P/N WO-4118L-07S (1.8 Step Motor)
24 Vdc, 1.05 Amp/Phase, IB462, 1/2 Stepping



CUI Devices P/N NEMA17-19-07PD-AMT112S
Lin Engineering P/N WO-4118L-07P (1.8 Step Motor)
24 Vdc, 2.1 Amp/Phase, IB463, 1/2 Stepping

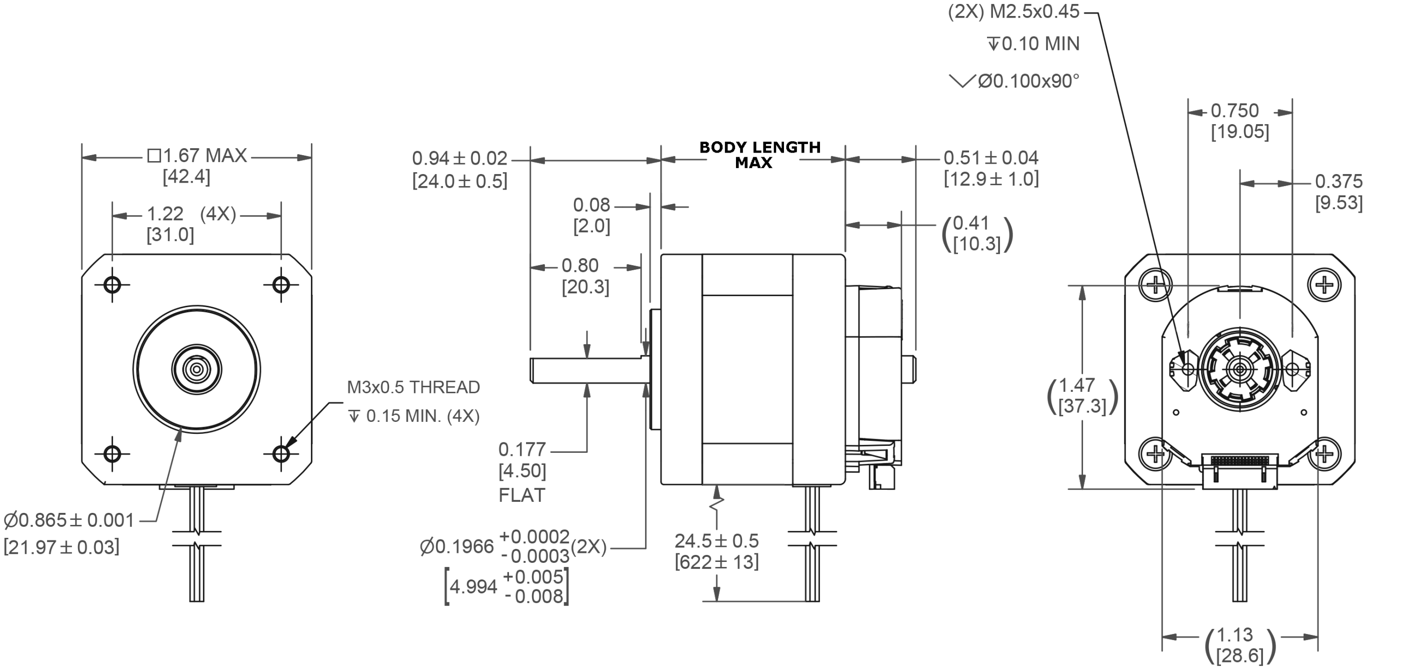


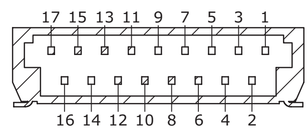
CUI Devices P/N NEMA17-23-01D-AMT112S
Lin Engineering P/N WO-4118C-01 (1.8 Step Motor)
24 Vdc, 2 Amp/Phase, IB463, 1/2 Stepping



MECHANICAL DRAWING

units: inch [mm]
tolerance:
X.XX ±0.01 [±0.25]
X.XXX ±0.005 [±0.13]
X.XXXX ±0.0005 [±0.013]





Mating Connector:
JAE FI-W17S

MOTOR WIRE CONNECTIONS	
Color	Function
red	A
blue	$\overline{A}$
green	B
black	$\overline{B}$
26 AWG[3], PVC	

MODEL NO.	BODY LENGTH (inch)	WEIGHT (lb)
NEMA17-13-04SD-AMT112S	1.34	0.50
NEMA17-13-04PD-AMT112S	1.34	0.50
NEMA17-16-06SD-AMT112S	1.58	0.65
NEMA17-16-06PD-AMT112S	1.58	0.65
NEMA17-19-07SD-AMT112S	1.89	0.80
NEMA17-19-07PD-AMT112S	1.89	0.80
NEMA17-23-01D-AMT112S	2.34	0.90

ENCODER CONNECTIONS	
#	Function
1	TX_ENC+
2	RX_ENC+
3	N/A
4	GND
5	N/A
6	+5 V
7	N/A
8	B+
9	N/A
10	A+
11	N/A
12	Z+
13	N/A
14	MCLRB
15	N/A
16	N/A
17	N/A

Note 3. NEMA17-19-07PD-AMT112S & NEMA17-23-01D-AMT112S models have 22 AWG wires.

REVISION HISTORY

rev.	description	date
1.0	initial release	06/26/2018
1.01	corrected datasheet typos	08/29/2019
1.02	brand update	02/20/2020

The revision history provided is for informational purposes only and is believed to be accurate.

DATASHEET

Raspberry Pi 4 Model B

Release 1

June 2019

Table 1: Release History

Release	Date	Description
1	21/06/2019	First release

The latest release of this document can be found at `https://www.raspberrypi.org`

Contents

List of Figures

List of Tables

1 Introduction

The Raspberry Pi 4 Model B (Pi4B) is the first of a new generation of Raspberry Pi computers supporting more RAM and with siginficantly enhanced CPU, GPU and I/O performance; all within a similar form factor, power envelope and cost as the previous generation Raspberry Pi 3B+.

The Pi4B is avaiable with either 1, 2 and 4 Gigabytes of LPDDR4 SDRAM.

2 Features

2.1 Hardware

- Quad core 64-bit ARM-Cortex A72 running at 1.5GHz
- 1, 2 and 4 Gigabyte LPDDR4 RAM options
- H.265 (HEVC) hardware decode (up to 4Kp60)
- H.264 hardware decode (up to 1080p60)
- VideoCore VI 3D Graphics
- Supports dual HDMI display output up to 4Kp60

2.2 Interfaces

- 802.11 b/g/n/ac Wireless LAN
- Bluetooth 5.0 with BLE
- 1x SD Card
- 2x micro-HDMI ports supporting dual displays up to 4Kp60 resolution
- 2x USB2 ports
- 2x USB3 ports
- 1x Gigabit Ethernet port (supports PoE with add-on PoE HAT)
- 1x Raspberry Pi camera port (2-lane MIPI CSI)
- 1x Raspberry Pi display port (2-lane MIPI DSI)
- 28x user GPIO supporting various interface options:
  - Up to 6x UART
  - Up to 6x I2C
  - Up to 5x SPI
  - 1x SDIO interface
  - 1x DPI (Parallel RGB Display)
  - 1x PCM
  - Up to 2x PWM channels
  - Up to 3x GPCLK outputs

2.3 Software

- ARMv8 Instruction Set
- Mature Linux software stack
- Actively developed and maintained
  - Recent Linux kernel support
  - Many drivers upstreamed
  - Stable and well supported userland
  - Availability of GPU functions using standard APIs

3 Mechanical Specification

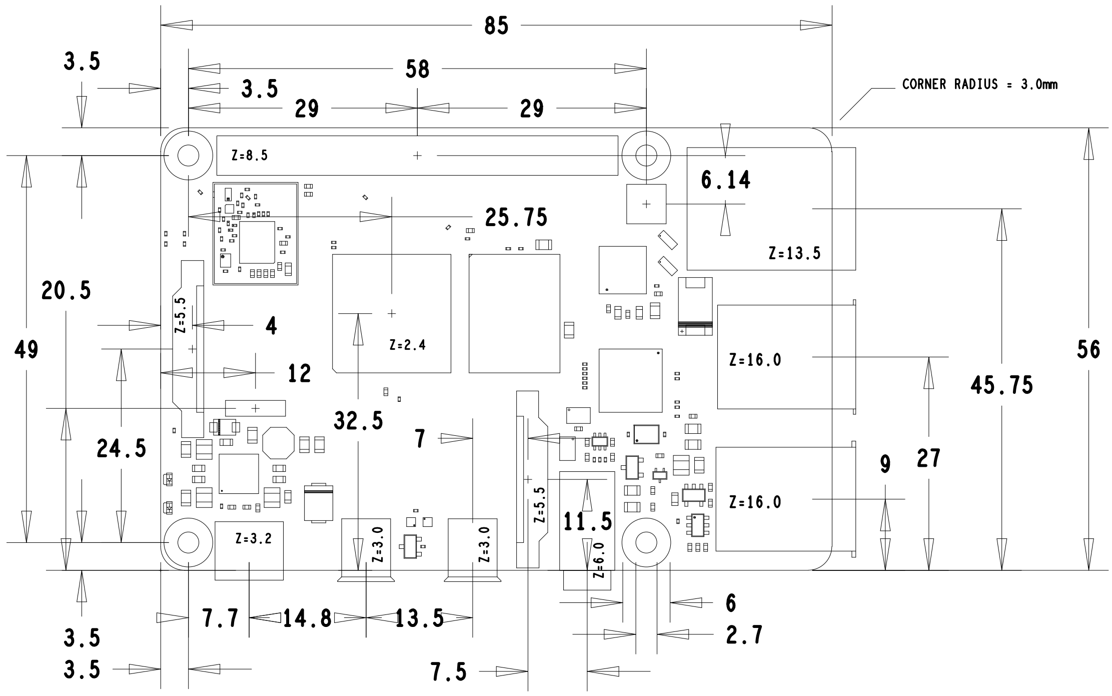


Figure 1: Mechanical Dimensions

4 Electrical Specification

Caution! Stresses above those listed in Table 2 may cause permanent damage to the device. This is a stress rating only; functional operation of the device under these or any other conditions above those listed in the operational sections of this specification is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

Symbol	Parameter	Minimum	Maximum	Unit
VIN	5V Input Voltage	-0.5	6.0	V

Table 2: Absolute Maximum Ratings

Please note that VDD_IO is the GPIO bank voltage which is tied to the on-board 3.3V supply rail.

Symbol	Parameter	Conditions	Minimum	Typical	Maximum	Unit
V_{IL}	Input low voltage[a]	VDD_IO = 3.3V	-	-	TBD	V
V_{IH}	Input high voltage[a]	VDD_IO = 3.3V	TBD	-	-	V
I_{IL}	Input leakage current	TA = +85°C	-	-	TBD	μA
C_{IN}	Input capacitance	-	-	TBD	-	pF
V_{OL}	Output low voltage[b]	VDD_IO = 3.3V, IOL = -2mA	-	-	TBD	V
V_{OH}	Output high voltage[b]	VDD_IO = 3.3V, IOH = 2mA	TBD	-	-	V
I_{OL}	Output low current[c]	VDD_IO = 3.3V, VO = 0.4V	TBD	-	-	mA
I_{OH}	Output high current[c]	VDD_IO = 3.3V, VO = 2.3V	TBD	-	-	mA
R_{PU}	Pullup resistor	-	TBD	-	TBD	kΩ
R_{PD}	Pulldown resistor	-	TBD	-	TBD	kΩ

[a] Hysteresis enabled
[b] Default drive strength (8mA)
[c] Maximum drive strength (16mA)

Table 3: DC Characteristics

Pin Name	Symbol	Parameter	Minimum	Typical	Maximum	Unit
Digital outputs	t_{rise}	10-90% rise time[a]	-	TBD	-	ns
Digital outputs	t_{fall}	90-10% fall time[a]	-	TBD	-	ns

[a] Default drive strength, CL = 5pF, VDD_IO = 3.3V

Table 4: Digital I/O Pin AC Characteristics

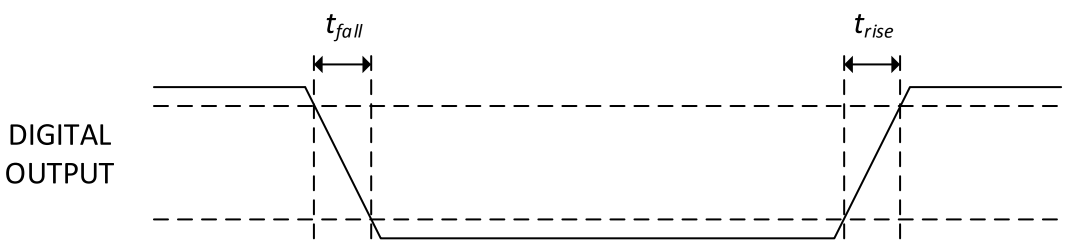


Figure 2: Digital IO Characteristics

4.1 Power Requirements

The Pi4B requires a good quality USB-C power supply capable of delivering 5V at 3A. If attached downstream USB devices consume less than 500mA, a 5V, 2.5A supply may be used.

5 Peripherals

5.1 GPIO Interface

The Pi4B makes 28 BCM2711 GPIOs available via a standard Raspberry Pi 40-pin header. This header is backwards compatible with all previous Raspberry Pi boards with a 40-way header.

5.1.1 GPIO Pin Assignments

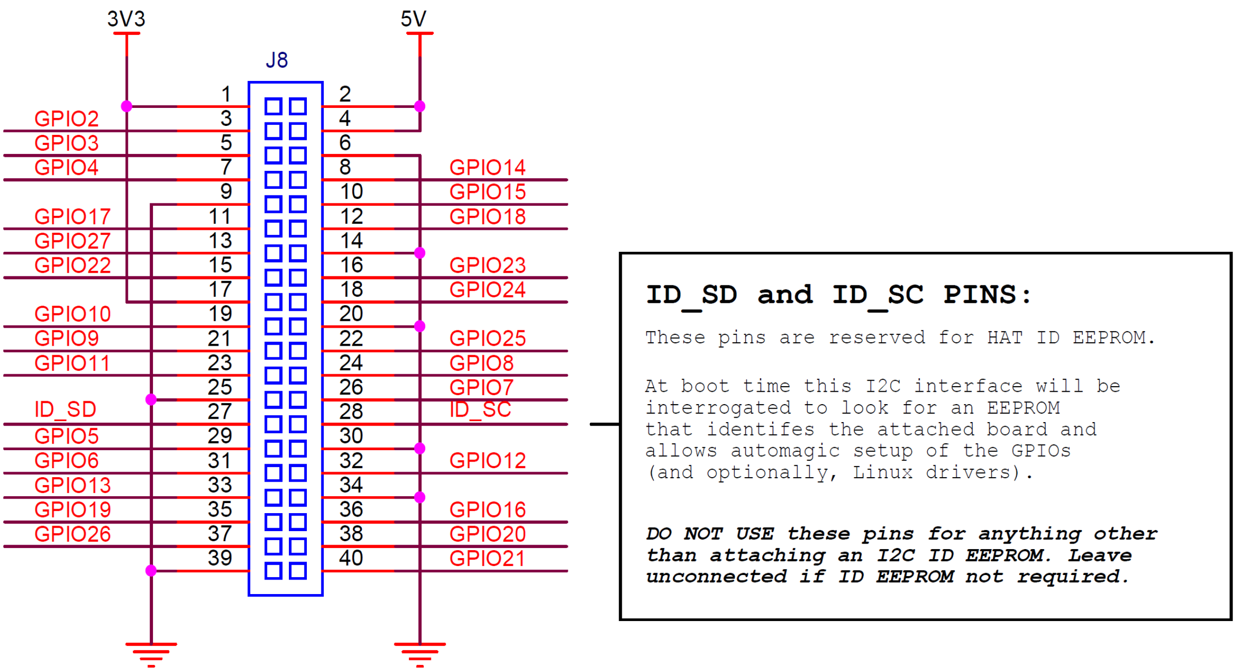


Figure 3: GPIO Connector Pinout

As well as being able to be used as straightforward software controlled input and output (with programmable pulls), GPIO pins can be switched (multiplexed) into various other modes backed by dedicated peripheral blocks such as I2C, UART and SPI.

In addition to the standard peripheral options found on legacy Pis, extra I2C, UART and SPI peripherals have been added to the BCM2711 chip and are available as further mux options on the Pi4. This gives users much more flexibility when attaching add-on hardware as compared to older models.

5.1.2 GPIO Alternate Functions

GPIO	Default Pull	ALT0	ALT1	ALT2	ALT3	ALT4	ALT5
0	High	SDA0	SA5	PCLK	SPI3_CE0_N	TXD2	SDA6
1	High	SCL0	SA4	DE	SPI3_MISO	RXD2	SCL6
2	High	SDA1	SA3	LCD_VSYNC	SPI3_MOSI	CTS2	SDA3
3	High	SCL1	SA2	LCD_HSYNC	SPI3_SCLK	RTS2	SCL3
4	High	GPCLK0	SA1	DPI_D0	SPI4_CE0_N	TXD3	SDA3
5	High	GPCLK1	SA0	DPI_D1	SPI4_MISO	RXD3	SCL3
6	High	GPCLK2	SOE_N	DPI_D2	SPI4_MOSI	CTS3	SDA4
7	High	SPI0_CE1_N	SWE_N	DPI_D3	SPI4_SCLK	RTS3	SCL4
8	High	SPI0_CE0_N	SD0	DPI_D4	-	TXD4	SDA4
9	Low	SPI0_MISO	SD1	DPI_D5	-	RXD4	SCL4
10	Low	SPI0_MOSI	SD2	DPI_D6	-	CTS4	SDA5
11	Low	SPI0_SCLK	SD3	DPI_D7	-	RTS4	SCL5
12	Low	PWM0	SD4	DPI_D8	SPI5_CE0_N	TXD5	SDA5
13	Low	PWM1	SD5	DPI_D9	SPI5_MISO	RXD5	SCL5
14	Low	TXD0	SD6	DPI_D10	SPI5_MOSI	CTS5	TXD1
15	Low	RXD0	SD7	DPI_D11	SPI5_SCLK	RTS5	RXD1
16	Low	FL0	SD8	DPI_D12	CTS0	SPI1_CE2_N	CTS1
17	Low	FL1	SD9	DPI_D13	RTS0	SPI1_CE1_N	RTS1
18	Low	PCM_CLK	SD10	DPI_D14	SPI6_CE0_N	SPI1_CE0_N	PWM0
19	Low	PCM_FS	SD11	DPI_D15	SPI6_MISO	SPI1_MISO	PWM1
20	Low	PCM_DIN	SD12	DPI_D16	SPI6_MOSI	SPI1_MOSI	GPCLK0
21	Low	PCM_DOUT	SD13	DPI_D17	SPI6_SCLK	SPI1_SCLK	GPCLK1
22	Low	SD0_CLK	SD14	DPI_D18	SD1_CLK	ARM_TRST	SDA6
23	Low	SD0_CMD	SD15	DPI_D19	SD1_CMD	ARM_RTCK	SCL6
24	Low	SD0_DAT0	SD16	DPI_D20	SD1_DAT0	ARM_TDO	SPI3_CE1_N
25	Low	SD0_DAT1	SD17	DPI_D21	SD1_DAT1	ARM_TCK	SPI4_CE1_N
26	Low	SD0_DAT2	TE0	DPI_D22	SD1_DAT2	ARM_TDI	SPI5_CE1_N
27	Low	SD0_DAT3	TE1	DPI_D23	SD1_DAT3	ARM_TMS	SPI6_CE1_N

Table 5: Raspberry Pi 4 GPIO Alternate Functions

Table 5 details the default pin pull state and available alternate GPIO functions. Most of these alternate peripheral functions are described in detail in the BCM2711 Peripherals Specification document which can be downloaded from the hardware documentation section of the website.

5.1.3 Display Parallel Interface (DPI)

A standard parallel RGB (DPI) interface is available the GPIOs. This up-to-24-bit parallel interface can support a secondary display.

5.1.4 SD/SDIO Interface

The Pi4B has a dedicated SD card socket which suports 1.8V, DDR50 mode (at a peak bandwidth of 50 Megabytes / sec). In addition, a legacy SDIO interface is available on the GPIO pins.

5.2 Camera and Display Interfaces

The Pi4B has 1x Raspberry Pi 2-lane MIPI CSI Camera and 1x Raspberry Pi 2-lane MIPI DSI Display connector. These connectors are backwards compatible with legacy Raspberry Pi boards, and support all of the available Raspberry Pi camera and display peripherals.

5.3 USB

The Pi4B has 2x USB2 and 2x USB3 type-A sockets. Downstream USB current is limited to approximately 1.1A in aggregate over the four sockets.

5.4 HDMI

The Pi4B has 2x micro-HDMI ports, both of which support CEC and HDMI 2.0 with resolutions up to 4Kp60.

5.5 Audio and Composite (TV Out)

The Pi4B supports near-CD-quality analogue audio output and composite TV-output via a 4-ring TRS 'A/V' jack.

The analog audio output can drive 32 Ohm headphones directly.

5.6 Temperature Range and Thermals

The recommended ambient operating temperature range is 0 to 50 degrees Celcius.

To reduce thermal output when idling or under light load, the Pi4B reduces the CPU clock speed and voltage. During heavier load the speed and voltage (and hence thermal output) are increased. The internal governor will throttle back both the CPU speed and voltage to make sure the CPU temperature never exceeds 85 degrees C.

The Pi4B will operate perfectly well without any extra cooling and is designed for sprint performance - expecting a light use case on average and ramping up the CPU speed when needed (e.g. when loading a webpage). If a user wishes to load the system continually or operate it at a high termperature at full performance, further cooling may be needed.

6 Availability

Raspberry Pi guarantee availability Pi4B until at least January 2026.

7 Support

For support please see the hardware documentation section of the Raspberry Pi website and post questions to the Raspberry Pi forum.