

Automatic Solder Paste Dispenser for Prototype Printed Circuit Boards



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Chapter 1 - Executive Summary

In just about every engineering endeavor by Electrical and Computer Engineers, designing and installing parts on a PCB is just a part of the job. Part of that installation process requires getting a tube of solder paste out, placing a custom stencil on the PCB, and smearing the pads of the PCB with enough solder paste for parts like capacitors, resistors, and IC chips to have a secure connection to the pads of the PCB after going through a reflow oven.

Many companies have seen this problem and have designed huge and expensive machines, mainly for other businesses, to help solve it. This leaves many people with personal projects left to their own devices and primitive techniques of applying solder paste properly on a PCB.

The SPD (Solder Paste Printer) offers that solution at a discount and more. The SPD places solder paste directly on the pads of a PCB given to it. For high usability with custom PCBs, the printer takes and converts the top layer of the Gerber file of the PCB to create a map of all the pads of the PCB. With the map of the pads, the printer will be able to precisely move stepper motors to each pad and dispense drops of solder paste. The printer also has a unique optical system. The optical system will take magnified pictures of each solder paste placement that the user can observe to ensure quality in the placements of solder paste on their PCB. Users will be able to export and view 3D reconstructions of the object area.

For interaction with the SPD, a website and touch screen will be utilized. The website will be hosted on a private network and allow users to upload Gerber files to the SPD and view the captured magnified photos of the solder paste deposits on their PCB. The touch screen will be used by the user to select their Gerber file and to start the print job with the file selected. The touch screen will also have a manual mode menu to manually control the position and printing of solder paste if needed.

With the SPD, depositing solder paste accurately and precisely can be done easily and seamlessly for projects with custom PCBs.

Chapter 2 - Project Description

2.1 Motivation and Background

Printed Circuit Boards (PCBs) are fundamental in a majority of modern systems. These crucial electronic components can be seen in everything from consumer applications to complex industrial equipment. From providing power distribution, enabling connectivity, and supporting the thousands of existing Micro Controller Units (MCUs) and Integrated Circuits (ICs). These components enable the modern world of technology that society has become accustomed to. However, the tools used to produce these PCBs are often out of reach unless you are a large multi-billion-dollar corporation. That is where our senior design project comes in.

Sponsored by Dr. Weeks, our goal is to modify an Ender 3 printer to dispense solder paste onto custom blank PCBs ordered by students. Previously, students had to apply the solder paste themselves, either by using stencils from manufacturers—an additional expense that often resulted in a messy process—or by manually dispensing the paste with a small dispenser tube and magnifications lens. Our proposed system will allow students to upload their PCB design files and have the solder paste automatically dispensed. Additionally, students will be able to inspect the quality of their PCBs. This solution aims to save students valuable time in the lab.

2.2 Existing Products

There is a wide range of existing products with features similar to the many systems in this solder paste dispenser. Some solder paste dispensers are manual, acting like a syringe, while others are automatic, similar to what the team will achieve. First, we will look at the basic manual dispensers, followed by some automatic dispensers, optical systems, and finally, some pick-and-place systems.

2.2.1 Solder Paste Dispenser Types

2.2.1.a Manual Solder Paste Dispensers

Manual paste dispensers are handheld and lightweight tools for various types of pastes, such as solder, glue, grease, and silicone. They are mostly operated by compressing air with a pump or using a motor to push out the paste from the tube. These dispensers also have different-sized tips for various levels of precision.

Manual solder paste dispensers like the ones sold by JBC Soldering are handheld devices resembling a syringe with an interchangeable solder paste tube. The solder is applied using the tip of the needle and a finger-contact point. When the

user presses down on the contact point, it applies pressure to the solder paste tube thus dispensing it out of the needle. When the solder paste tube is depleted, a new tube can simply be inserted into the slot where the old tube sat. JBC also sells other products to support the manual paste dispenser such as bent needles for different angles of dispensing [1]. There are two types of tips used on the JBC manual solder paste dispenser, either a stainless-steel dispensing needle or a tapered plastic tip. The precision on the steel needles ranges from Type 2 solder paste at Gauge 18 (0.84mm / 0.033 in) to Type 6 solder paste at Gauge 30 (0.15 mm / 0.006 in) [2]. The precision on the tapered tips ranges from Type 2 solder paste at Gauge 18 to Type 5 at Gauge 27 (0.20mm / 0.008 in) [3]. These various tips allow the user to alter its precision based on the SMD package size requiring solder paste.

There is another type of manual solder paste dispenser called the I-Extruder Solder Paste Dispenser with Pick & Place feature, which is powered (via USB or power bank) and can dispense with the press of a button. It includes an OLED display with settings, buttons to navigate the settings in the display, a stepper motor which helps act like a pump, a release ring for switching syringe sizes, buttons to control the pressure direction for dispensing and suction, and finally different tips. The pick and place feature enables a suction cup to be attached to the extruder as the user presses the button for suction. This allows the device to place 0402 SMD package sizes. The I-Extruder had a charging port in the back along with a trigger port that allows a footswitch to be connected to it, allowing for more accessibility to the user [4].

The Digital Precision Fluid Dispenser SRA #205 is a pneumatic electric solder paste dispenser. This dispenser requires an external air compressor powered by house voltage that leads into the handheld dispenser. The external air compressor has a display and features different timed modes to help control the flow of fluids. In addition, it also has a “vacuum pullback control” which prevents too much fluid from leaking out when the user stops dispensing. This pneumatic dispenser can output 1-100 PSI based on the user’s input and has multiple tip sizes for various precisions. Similar to the previous device, it includes a foot and a finger trigger for dispensing. It can be used for solder paste, epoxy, lubricants, etc. [5].

On the topic of manual and handheld devices, there is another pick and place system that can be used in conjunction with these solder paste dispensers. The PK Unit Pick & Place from JBC is a vacuum unit designed for picking up SMD components and placing them on a PCB after solder paste has been applied. It has a handle and a pedal for foot control along with various bent needles, straight needles, and suction cups to place on the needles. It also includes a continuous drive mode for removing components [6]. As discussed in the coming sections, this would be an advanced goal for the team to be able to realize in this project.

2.2.1.b Screen/Stencil Printers

The solder paste screen/stencil printer was one of the first machines in the assembly line for the Surface Mount Technology Industry creating a major impact in the commercial space. The screen printer with the use of a metal stencil enables automation of equally distributing solder paste on PCB (Printed Circuit Board) pads evenly and ready for pick and place machines which place surface components on the PCB.

The solder paste screen printers place and align a PCB, and an etched metal stencil on top. Then, a squeegee comes across pushing solder paste at around a sixty-degree angle moving back and forth on top of the stencil to evenly distribute solder paste on the PCB pads [7]. The squeegee is pulled back and the stencil is lifted off the PCB. The PCB is moved out of the way for another PCB to be printed on next.

MPM has a very accurate screen printer, the Edison II ACT Stencil Printer. Its wet print reliability is high, ± 15 microns, and greater than or equal to 2 Cpk (Process Capability Index) at six-sigma [8]. The printer is high-speed and has short cycle times leading to a higher output of PCBs ready for pick and place machines.

The YRP10 screen printer is made by Yamaha. The wet print reliability for the screen printer is like the Edison II ACT Stencil Printer, ± 16 microns and greater than or equal to 2 Cpk at six-sigma [9]. It features a dual-lane setup as each machine has two separate parallel conveyor belts, the printing belt, and the pass-through belt. If two machines are placed with belts in line and the fronts are in opposite directions, then two printing lanes can be made to increase print production [9]. The squeegee head's attack angle can be modified as well. It also features a stencil vacuum which presses the stencil to the PCB for a more accurate print.

The Momentum II Elite Stencil Printer is another MPM screen printer. Its wet print reliability is high, ± 20 microns and greater than or equal to 2 Cpk (Process Capability Index) at six-sigma [10]. This is worse than the other two mentioned, but it has many features. The printer includes triple-track processing which means that while it is processing/printing on one PCB then the previous PCB is being offloaded and another one is being loaded to increase throughput [10]. It also has AccuCheck Print Capability Verification which is very useful as it can continuously monitor and measure the print capability of the machine. Another great feature is the vision and

inspection system which verifies the printer is working accurately and that the printer is giving great results [10].

The process of stencil/screen printing is very effective but still has some challenging problems. Some of the difficulties include scooping, bleeding, bridging, and peaking [11]. These issues refer to different ways solder paste is misplaced where too little or extra amounts of solder paste are left on the PCB. They come about more frequently in stencil/screen printing. The issues can be mitigated by a different solution.

2.2.1.c Jet Printers

Jet printing arrived after screen printing to help make the solder paste placement process easier and faster. Jet printers take a PCB's Gerber file to make a map of pads of the PCB [12]. Then, motors move a nozzle over each pad systematically to inject solder paste without the use of a stencil. After, the next PCB inline is printed.

Essemtec made the Archerfish which is another jet printer. It is very fast and can place solder paste dots as fast as seven hundred twenty thousand dots per hour and the minimum dot size possible is 200 microns [13]. The jet printer also comes with the capability of glue jetting and is its own pick-and-place machine [13]. A system in place in the machine monitors solder paste sizing by volume and weight.

Voltera's all-in-one PCB manufacturing and assembly machine, the Voltera V-One, provides consumers with a fast way to manufacture, assemble, and prototype custom PCBs. The machine can drill vias/holes and draw traces removing the need to outsource PCB manufacturing [14]. It also features a heat reflow bed eliminating the need to use an oven to reflow the solder after assembly [15]. However, the V-One does not offer any functionality for design inspection and verification.

2.2.1.d Summary: Application of Solder

After looking at how these manual dispenser and printers work, we will be taking more away from how these jet printers work in our designs. There are features we are looking to emulate from jet printers. These features include using a Gerber file to map the PCB pads and using motors and a nozzle to dispense the solder paste. Utilizing the Gerber file makes our design user-friendly. It is user-friendly because when a PCB is designed the Gerber file is made which includes all the information a PCB manufacturer would need including the PCB's pad's locations and size. Also, dispensing solder paste from a nozzle that is controlled by motors will lead

to a cheaper and cleaner process. Without this design choice, the alternative is having extra costs for the purchase of a stencil and a messy process of applying solder paste to the PCB pads.

2.2.2 Existing Optical Inspection Systems

In general, optical inspection systems are systems that include sensors, lenses, and sometimes optomechanical parts for variable magnification. They are used for general inspection tasks that are involved in manufacturing and quality assurance processes which ensure reliability and repeatability. All these products take advantage of digital magnification and sometimes include magnification optics as well. The following paragraphs will look at various optical inspection systems for different applications.

2.2.2.a EVOTIS by *Vision Engineering*

EVOTIS by Vision Engineering is a manually operated optical inspection system that provides features for methodical inspection of critical PCBs. The system offers 3-765x magnification utilizing optical and monitor magnification. It features a monitor for viewing and easy camera placement. The system has a 360-degree 3D stereo-rotating viewer that can capture every detail from every angle efficiently. The system features easily switchable white and UV lights for inspections. It can handle a maximum board size of 460 mm x 460 mm. The system consists of a monitor with a vertical camera system that is pointed down and vertically towards an inspection baseplate where the user can place their PCB under question. The EVOTIS system is a versatile, capable system for careful inspection of critical PCBs. [16]

2.2.2.b Macro Vue Eidos by *Aven Tools*

The Macro Vue Eidos Inspection System by Aven Tools is a robust digital inspection system. This system features a 1920 x 1080 resolution FULL HD Panasonic 1/2.8" sensor with 3.5x to 35.5x magnification. It features LED lighting with brightness control and a monitor for viewing the output of the camera. This system only offers 2D imaging and does not feature any stereo vision system. It also features a built-in SD card port for easy image capture, as well as USB for computer connectivity. These systems are useful for inspecting a variety of things, not just limited to inspection of PCBs. They can be used to inspect small mechanical parts. The system is expensive and costs \$2,347.26. This system is only one of a variety of products Aven Tools offers. They vary in price range and the applications they can be used for. [17]

2.2.2.c W30 EasyView 4K Inspection System by Optilia

The W30 EasyView 4K Inspection System offers first class inspection. It features a 30x optical zoom with fast and responsive auto focus which makes it easier for operators to keep their area of interest in focus. It features a 4K resolution sensor and comes with built-in illumination which illuminates the subject evenly for high-quality images. It does not come with a monitor but features a port to connect to a monitor. The camera sits on a boom and is vertical and is pointed down, looking at the baseplate under it. To maneuver the camera, the user utilizes a joystick making it easy to place the camera where necessary. The system varies in price depending on optional upgrades but ranges from \$5000 - \$7000. [18]

2.2.2.d iS6059 PCB Inspection Plus system by Viscom

The iS6059 PCB Inspection Plus system by Viscom is an automated optical inspection system used to rapidly check electronic components on PCBs. The system is primarily designed for in-line quality assurance purposes. The system features optical inspection that provides reliable and fast measurements of height. The system features an XMplus-II 3D camera system that consists of one orthogonal and eight inclined cameras. This enables measuring height using stereo vision. The optical system has field of view size of 50 mm x 50 mm. The camera can resolve a z-resolution of half a micron. The maximum PCB size the system can support is 508 mm x 508 mm. This system provides fast, accurate and reliable PCB inspection leveraging stereo vision and artificial intelligence algorithms. To get a price on the machine, we would have to ask for a quote and get an estimate. [19]

2.2.2.e SQ3000+ by Nordson

The SQ3000+ automated optical inspection system by Nordson is a large machine offering ultra-high resolution at 5 μm with a height resolution of 0.1 μm . The system is powered by CyberOptics' proprietary 3D sensing technology that results in ultra-high-quality 3D images. The system also features Multi-Reflection Suppression (MRS) technology that improves the system's accuracy by identifying and rejecting reflection-based distortions caused by shiny components. The system can inspect 16 square centimeters per second. It can support a maximum PCB size of 420 mm x 320 mm. The maximum weight of a PCB sample is 10 kg. The system has a minimum component size of 0201 mm and a field of view of 25 mm x 25 mm. The system is seamless when it comes to reliable inspection of PCBs.

2.2.2.f IM-8005 Series by KEYENCE

The IM-8005 Series system by KEYENCE is an image dimension measurement system used for inspecting 3D physical parts for making quick schematics. The

system is primarily used for inspecting parts, but it can also be used for inspecting PCBs. The system offers fast and reliable measurements. The user places their part on the bed for measurement. To take the measurement the user simply presses a button, and the machine automatically takes measurements of different physical features, automatically. The system does not feature a stereo vision system to measure height. The height is measured using a contact height measurement unit. As a result, the system uses a telecentric lens that is not affected by height differences, this ensures accurate edge detection and feature measurements. The IM-8005 is one of a series of IM-8000 systems that all come with different options and configurations for different types of applications. [20]

2.2.2.g SS15000PAL by AOI Systems

AOI Systems offers automated optical inspection for PCBs. Their machines can also be used at a manufacturing and quality assurance level for quick PCB inspection. These machines can quickly inspect PCBs. They do this by utilizing a scanner to quickly get a high-resolution image of the PCB, in sections, and then software is used to quickly compare sections of the PCB using an image comparator. AOI System's "ScanSpection" utilizes two separate, basic algorithms to inspect components and quality of soldering. These desktop scanners are useful for quick and reliable in-line inspection and output either a "pass" or "fail" for the board under question. Specifically, the SS15000PAL system can detect and identify typical board manufacturing defects, like a shifted or misplaced component, by using the image comparator. This system has a maximum board size of 630 mm x 495 mm and can inspect an area of 420 mm x 330 mm once at a time. The resolution of the machine is 20 μm by standard but they offer a 10 μm option. [21]

2.2.2.h 400 Series Desktop Inspection and Measurement Systems by Vision Gauge

Vision Gauge offers a variety of desktop inspection and measurement systems that are primarily used for inspecting mechanical parts. These machines use optics to inspect and measure the dimensions of parts and the machine can check the part if it meets tolerances. Vision Gauge's compact desktop optical comparator has a large measurement area of 12" x 12" and their 400 series inspection machines offer 3 axis inspection and measurement. The system features single magnification and precision optics with extended depth-of-field to keep regions of interest in focus. For height measurements, their systems can be equipped with an optional laser module that enhances the accuracy of height and depth measurements in the Z axis. However, these are not the only options that can be added. The machines can be outfitted with a variety of modules for specific customer needs. [22]

2.2.2.i OASIS Elite Inspection System by *OASIS Inspection Systems*

OASIS Inspection Systems offer a line of different optical inspection systems that vary in size to accommodate varying sizes of physical parts. These products offer fast, accurate, and easy inspection. This line of products includes the OASIS Elite, Elite Dual, Core, and Core X2. We will focus on their OASIS Elite product that is described as a 2D measurement optical inspection system with a fixed field of view. This product features a single camera that can take images of a part standing vertically or the machine can rotate such that you have a flat, transparent base to place parts on. The machine takes measurements by taking images of the optical profile of the part, makes measurements, and then finds where the part is not meeting tolerances. The system features an accuracy of 1 mil. However, the machine only takes the images, and the operator must make measurements in the software. [23]

2.2.2.j O-INSPECT by ZEISS

The O-INSPECT by ZEISS is a jack-of-all-trades vision measuring machine and optical inspection system. The O-INSPECT system features multi-sensor technology paired with optics to provide accurate machine vision measurements. The machine integrates optical inspection, 3D-vision and contact measuring methods into one machine. The system provides reliable 3D accuracy that complies with ISO standards. The O-INSPECT comes in different variants which are specific to the size of components that are to be inspected. [24]

2.2.2.k Summary: Optical Inspection Systems

After investigating the variety of optical inspection systems, we can see what features we would like to include in our system. Each system is different in functionality and autonomy. We have reviewed complex systems designed for on-the-line, fast, accurate, and autonomous operation. We have reviewed desktop systems designed for simple inspection purposes. We have seen systems that utilize 3D cameras. For our system, we want accuracy, reliability, and robustness. For quality inspection, we will utilize a stereo pair of cameras for visual inspection as well as for reconstructing the scene to a 3D point cloud. As a stretch goal, it is possible that the stereoscopic reconstruction will be done in real-time with a real-time output. This would be useful for users since they will be able to easily visualize the features on their PCB.

2.3 Goals and Objectives

The primary goal of this project is to build a solder paste dispenser for prototype printed circuit boards (PCBs) using an Ender 3 3D printer for reference. The basic goals and objectives are listed below:

Basic Goals:

- Create a solder paste dispenser utilizing the Creality Ender 3
- Implement a schematic/Gerber file upload system using a USB port and/or SD card reader
- Determine the user's PCB placement using an L-bracket and a square as the origin
- Dispense the proper amount of solder based on the uploaded schematic's required surface mount size
- Achieve an SMD package size of 0603(imperial)/1608(metric)
- Design an optical inspection system for stereo vision and magnification.
- Assemble optical magnification modules
- Use and program the Touchscreen display to provide the user with more customizability

Advanced Goals:

- Achieve more precise SMD package sizes such as 0402(imperial)/1005(metric)
- Complete the dispensing process within around ten minutes, on the maximum supported PCB size.
- Develop image processing software to allow users to export the 3D representation of the area

Stretch Goals:

- Achieve smaller SMD package sizes such as 0201(imperial)/0603(metric) - 01005(imperial)/0402(metric)
- Implement a pick-and-place system to grab components and place them on the newly dispensed solder paste
- Set up additional sensors or camera vision to help determine the origin point and structure of more uniquely shaped PCB designs (circular, L-shaped, etc.)
- Establish Wi-Fi or Bluetooth modules for schematic upload option and 3D model exports

Objectives:

Objectives to achieve Basic Goals:

Despite solder paste dispensers bearing many similarities to a 3D printer, the project must be differentiated enough for it to consider all of the design requirements of Senior Design. For the basic goal objectives, a custom PCB will have to be CAD-designed and printed along with custom software that must be programmed into the selected microcontroller. The custom PCB will include redesigned industry motor drivers, stepper motors, a power source, and a microcontroller. Alongside the software, there will be a schematic file upload system using an external USB port and/or an SD card reader that is connected to the microcontroller on the custom PCB. The device will be able to locate where the user has placed their own prototype PCB within the dispensing area by utilizing an L-bracket to set its origin point. Based on the user's uploaded schematic, the stepper motors will be activated to help the nozzle navigate and dispense the proper amount of solder paste. The main SMD package size that the team is trying to achieve is 0603(imperial) / 1608(metric), which equates to 1.6mm x 0.8mm. The team also seeks to prioritize the design of an optical inspection system that utilizes magnification and stereoscopy to create a 3D representation of the prototype PCB and the dispensing area. The team plans to make this controllable via a touchscreen display that will present all of this information.

To summarize:

- Create custom, ECAD-designed PCB
- Redesign motor driver into its own PCB
- Connect PCB to stepper motors, power supply, stereoscopy system, touchscreen display
- Implement schematic file upload system using external USB port and/or SD card reader
- Locate user's prototype PCB using L-bracket and stereoscopy system
- Dispense solder paste at SMD package size 0603(imperial) / 1608(metric)
- Display all information on touchscreen display

Objectives to achieve Advanced Goals:

One of the more technically complex objectives that the team is planning to deliver includes achieving a smaller SMD package size of 0402(imperial) / 1005(metric), which equates to 1.0mm x 0.5mm. The dispensing time would ideally be under ten minutes, this is a task that must be tested and optimized after fulfilling the basic goals and objectives. The aforementioned optical inspection system would also need software to be able to generate and export the 3D representation of the prototype PCB and dispensing area. This would be done on the same USB or SD card that the user initially inserted for the purpose of uploading their schematic.

To summarize:

- Dispense solder paste at SMD package size 0402(imperial) / 1005(metric)
- Perform and finish dispensing in under ten minutes for prototype PCBs within our maximum supported size.

- Generate and export 3D representation of prototype PCB

Objectives to achieve Stretch Goals:

Upon completion of the main and advanced objectives, the stretch objectives would include achieving an even smaller SMD package size anywhere from 0201(imperial) / 0603(metric) to 01005(imperial)/0402(metric), which respectively equates to 0.6mm x 0.3mm and 0.4mm x 0.2mm. Alongside the higher precision, an additional feature that would expand the purpose of the solder paste dispenser is a pick and place system. This system would be able to utilize a pump that would pick up components that the user plans on placing on their prototype PCB. Since the schematic for the PCB would already be uploaded, the pick pump would then place the components on the newly dispensed solder paste. The stereoscopy system would also be expanded upon with additional cameras or sensors in order to determine the structure and origin points of more uniquely shaped PCB's. This would allow the solder paste dispenser to accurately operate on a wider range of PCB's. Finally, the team would attempt to utilize the Wi-Fi and Bluetooth modules on the selected microcontroller for prototype PCB schematic uploads. This would extend the user's options for uploading to include USB port, SD card reader, Wi-Fi support, and Bluetooth support. The 3D representation of the prototype PCB could also be exported to the user via Wi-Fi or Bluetooth upon realization.

To summarize:

- Dispense solder paste at SMD package size 0201(imperial) / 0603(metric) to 01005(imperial)/0402(metric)
- Implement pick and place system utilizing pump
- Expand stereoscopy system to determine origin points of differently shaped PCBs
- Implement/utilize Wi-Fi module and Bluetooth support for schematic upload

The purpose of the Solder Paste Dispenser project is for this to be utilized within the Senior Design laboratory once the team has completed it. This machine will help other, future senior design students assemble their own prototype PCBs at the University of Central Florida. The team wants to provide a simple and cheap alternative for putting together PCBs through the use of precise stepper motors, rather than going through the strenuous process of applying solder paste by hand and squeegeeing out the excess amount. Ideally, the Solder Paste Dispenser would be able to dispense all the necessary solder paste within around ten minutes for a single PCB and allow students to inspect and verify the quality of their PCBs.

2.4 Features and Functionality

The SPD team aims to rebuild and modify an Ender 3D printer for the purpose of dispensing solder paste onto custom PCBs. The rebuilt printer will have a variety of features and functionalities used for operation, design inspection and verification.

2.4.1 General Operation

To operate the SPD, the user will upload a Gerber file of their custom PCB to the printer. This will be done using a USB or an SD card. The software will take the custom PCB Gerber file and convert the location information on the file into movements that will be communicated to the printer. After positioning the PCB, the user will interface with a touchscreen to command the printer to begin. Using the touchscreen, users will be able to start the printer, upload and select files, move the head of the printer manually, and export files to the connected SD card or USB stick.

To ensure the printer can determine the location of the custom PCB, PCBs will be slotted into an L-bracket. The printer's movements will all be relative to the origin established by this L-bracket. To prevent the PCB from slipping and moving during solder dispensing, a rubber mat will be used to provide grip. This will hold the custom PCB in place and prevent errors in dispensing.

2.4.2 Design Inspection and Verification Features

For PCB design inspection and verification, the SPD will include two sensors equipped with optics mounted on the dispenser. This enables the user to check the quality of dispensing with a magnified image. This optical system will also include an image processing system to produce a stereoscopic 3D representation of the imaged area. The user can then export this file to a 3D modeler. This provides the user with the tools to inspect their custom PCBs.

2.5 Required Specifications

Board Handling	
Maximum Board Size ($\hat{x}$ x $\hat{y}$)	8" x 8" / (203.2mm x 203.2mm)
Minimum Board Size ($\hat{x}$ x $\hat{y}$)	1" x 1" / (25.4mm x 25.4mm)
Board Securing Method	Rubber mat
Touchscreen	
Touchscreen Reactiveness*	Registers 95% of light touches
Print Parameters	

Maximum Print Area ($\hat{x} \times \hat{y}$)	200 mm x 200 mm
Solder Dispensing Resolution*	0.2 mm
Minimum Surface Mount Size	0603 (imperial) 1608 (metric)
Dispenser Head Movement Resolution ($\hat{x} \times \hat{y} \times \hat{z}$)	0.1 mm
Optical System	
Image Area	5 mm x 5 mm (7.07 diagonal length)
Total Magnification*	100x
Minimum Surface Mount Size for Imaging	0603 (imperial) 1608 (metric)
Stereoscopic Height Resolution	0.01 mm
Minimum Depth of Field	1 mm
Minimum Resolution	25 μ m
Facilities	
Power Requirements	120V AC
Machine Dimensions ($\hat{x} \times \hat{y} \times \hat{z}$)	45 cm x 45 cm x 50 cm

Table 1 : Required Specifications

*Demonstratable

2.6 Hardware Block Diagram

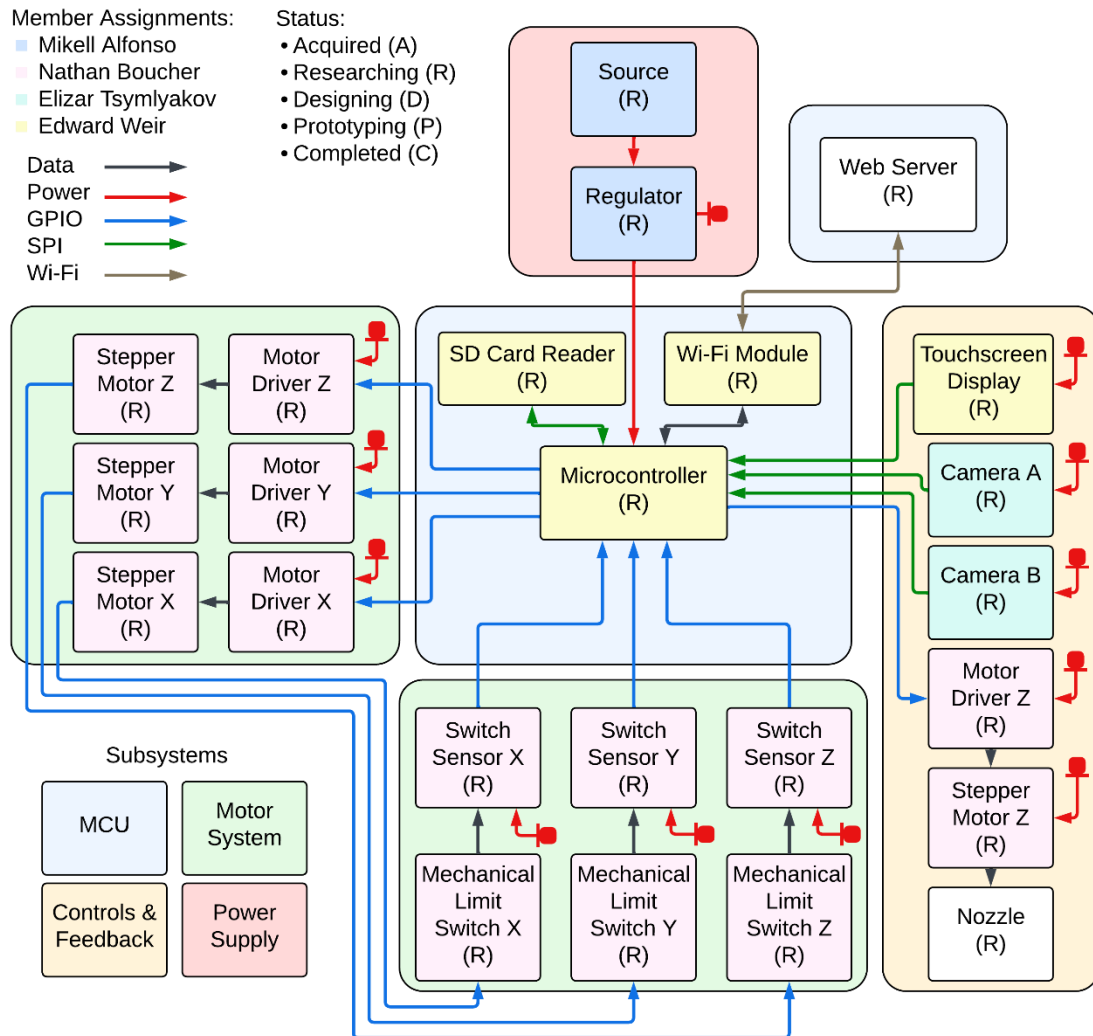


Figure 1: Hardware Block Diagram

2.7 Software Flowchart

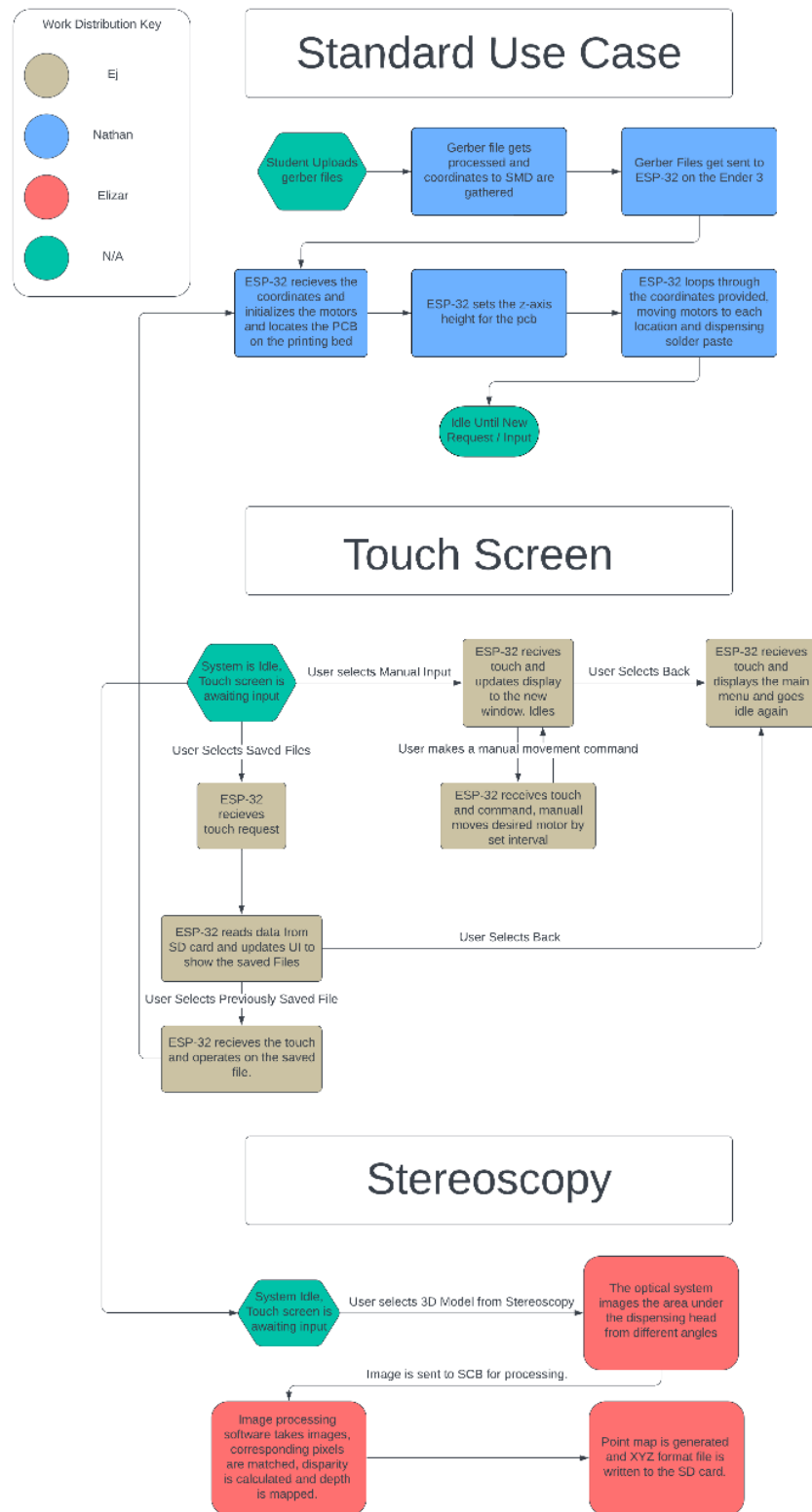


Figure 2: Software Flowchart

2.8 Optical Diagram and Design Requirements

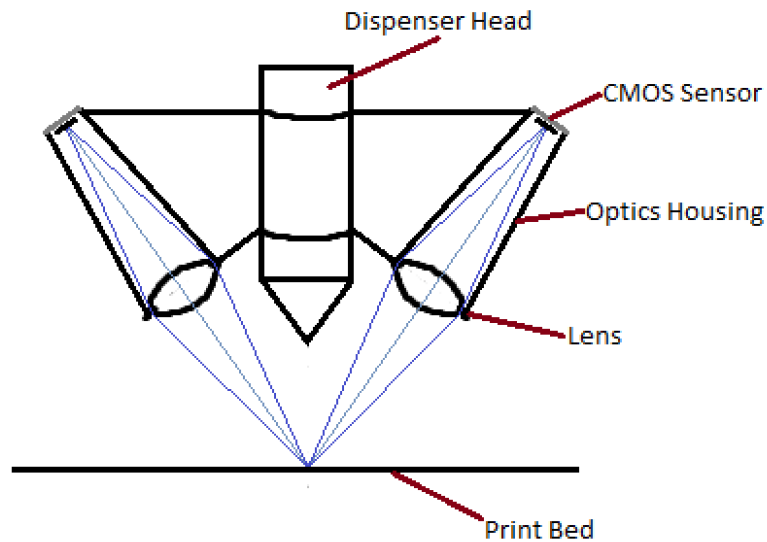


Figure 3: General view of the optical system.

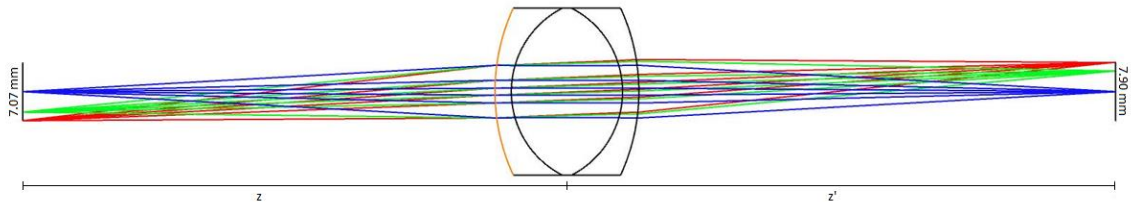


Figure 4: Optical diagram of one assembly.

2.8.1 Optical Design Requirements

This optical system must be designed with an image area of 5 mm x 5 mm (7.07 mm diagonal) and the proper magnification to cover the selected sensor adequately. The necessary magnification will be determined by taking the ratio of the diagonal lengths of the image area and sensor area: $M = (\text{sensor diagonal}) / (\text{image diagonal})$. For our current selection, we have a sensor with a diagonal of 4.6 mm. To cover the sensor adequately, we need the magnification to be $\sim 0.65\times$. This optical magnification gives us 1:1 imaging of the region. The 100x magnification is obtained by the ratio between typical computer monitor pixel size and sensor pixel size.

To reduce cost and manufacturing complexity, imaging and magnification will be achieved using a single lens. The lens will collect and focus the light onto the sensor and the magnification obtained depends on the distance between the object

and the lens (z) relative to the distance between the lens and the image (z') where $M = z'/z$. So, $z' = 0.65 * z$.

A minimum resolution of 25 μm was chosen, as this is the thinnest basic trace that we may encounter in custom PCBs made by students. To ensure our lens can resolve a 25 μm feature, we apply the Rayleigh criterion, which defines the smallest resolvable distance between two point-spread functions (PSFs). PSFs represent the distribution of light intensity after it passes through an aperture. In our case, with a circular lens (or circular aperture), the transfer function of the lens is a pupil function, producing an intensity profile resembling a sinc function. The width of this profile depends on the lens diameter and the wavelength of the light used. By applying the Rayleigh criterion, we can calculate the minimum numerical aperture (NA) required to resolve 25 μm . For a wavelength of 700 nm, a lens with an NA of at least 0.0183 is needed. The NA relates to the lens's diameter and focal length, where NA is equal to the diameter over twice the focal length.

In order to reliably image the features on the PCB for stereoscopic 3D reconstruction, we need to ensure that we have an adequate depth of field. This is because features on the PCB have varying heights and distances from the camera. Some features may be too far to be in focus, some features may be too close to be in focus. If we want to keep all these features in focus, we must ensure that our depth of field is long enough to successfully image most features we may encounter. Considering that the cameras will also be tilted for stereoscopy, it is critical to have sufficient depth of field. For sufficient imaging, we require a depth of field of 1.0 mm. Depth of field can be achieved by using a slower lens or by using an aperture to raise the f-number.

To achieve stereo imaging, two identical camera modules will be placed at a distance apart and at an angle such that they image the same location but from two different perspectives. The distance between the cameras is referred to as the baseline. The angle of viewing between the cameras, β , will be determined by the object distance and the distance between the lenses of the magnification modules, which depends on the thickness of the dispenser head. The optimal angle of the cameras relative to the baseline is 60-80 degrees. [25]

2.9 Prototype Illustration

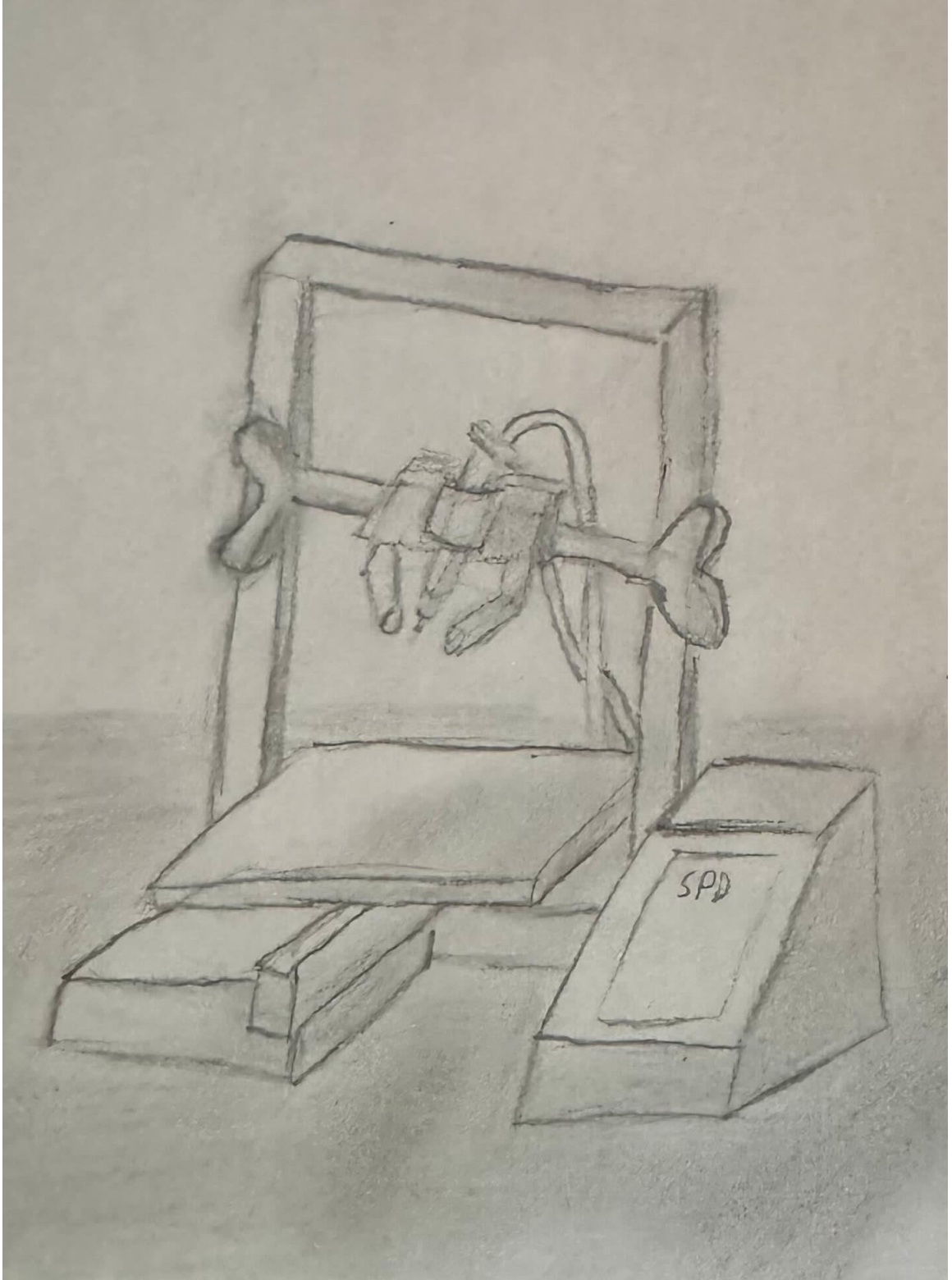


Figure 5: Prototype Illustration

2.10 House of Quality

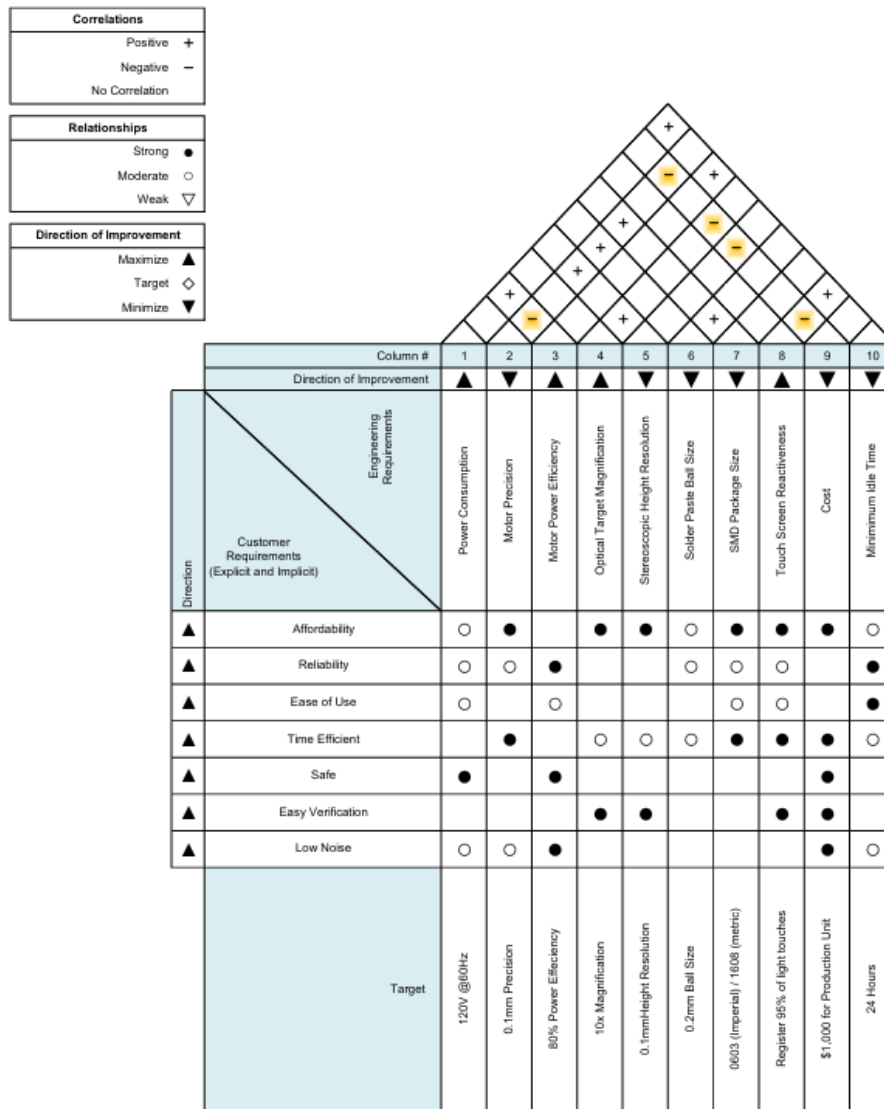


Figure 6: House of Quality

Chapter 3 – Research and Investigation

3.1 Hardware

3.1.1 Microcontroller Unit Selection

The Microcontroller Unit (MCU) will be the brain of our project. It will control the movements of the motors, sense the edge of the printing bed from the switches,

create a display on the TFT touchscreen and react to user touch, and monitor the status of each job. Without a functioning MCU there will be no functioning design, just a mechanical shell. The most important factors that are required to be researched when selecting an MCU are: number of GPIO Pins, number of ADC Pins, touch capacitive capability, amount of memory, low-power options, wireless connectivity options, CPU frequency, and the number of cores.

Having a sufficient number of GPIO pins is essential in order to control all devices, with enough of these being connected to the MCU's internal ADCs in order to read and parse data from analog signals, for example being able to sense touching on the touchscreen. Memory is another important aspect as our project has many moving parts, we need enough memory to store all of our applications data. Low-power options allow us to keep our device running efficiently, especially while in a sleep or inactive mode. Wireless connectivity will allow our design to be able to communicate to other devices easily. The CPU frequency relates to the number of clock cycles the CPU runs within a given second. Having a higher frequency allows for faster operation and processing. Likewise having multiple cores allows the MCU to run multiple options in parallel, increasing our designs computing speeds.

3.1.1.a ESP32-WROOM-MD

The ESP32-Wroom-MD is part of the ESP32 family of Microcontrollers from Espressif. The ESP32-Wroom-MD has a dual core processor that runs on an adjustable frequency of 80MHz to 240MHz [26]. It also has a low-power co-processor that can run in a “sleep” mode while waiting for input from peripherals. The ESP32-Wroom-MD comes with a built-in module for use of WiFi and Bluetooth (including BLE). This allows for better connectivity with other devices and the IoT. The ESP32 supports a data rate of up to 150Mbps [26]. The sleep current is also 5 microAmps allowing to stay powered by an external battery for an extended period.

The ESP32 has 38 pins [26] allowing for a wide number of peripherals to be connected. The ESP32 natively supports communication protocols such as UART, I2C, SPI, I2C, PWM, and I2S. This allows for connectivity to the peripherals we need such as the SPI interface required for the SD Card and Cameras, as well as GPIO pins with PWM ability to control the Stepper Motor Drivers. As well as ADC pins used for capacitive touch sensors.

3.1.1.b MSP430F6459

The MSP430F6459 is part of Texas Instrument's MSP430 series of microcontrollers. It is an ultra-low-power microcontroller with a 16-bit Reduced

Instruction Set Computer (RISC) CPU [27]. It operates on a frequency of 20MHz, and it has a single core. The MSP430F6459 comes with 512 kBytes of non-volatile memory and 66 kBytes of traditional RAM (volatile memory) [27]. It comes with a 12-bit Successive Approximation (SAR) ADC, that has 12 channels allowing for lots of peripherals to utilize. It has 74 GPIO pins. These GPIO pins has 3 pins for UART, 3 pins for I2C, 6 pins for SPI, and 4 16-bit timers [27]. It operates on a low supply voltage of 1.8V-3.6V, and natively supports a standby mode in order to be energy efficient while waiting for tasking. It also supports a USB serial bus, allowing for easy flashing and communication with other devices. However, it does not natively come with any support for wireless communication, an additional IC will be required to support wireless communication such as Wi-Fi and Bluetooth. At a price of \$11.929 it is an affordable option.

3.1.1.c RP2350B

The RP2350 is a series of microcontrollers by Raspberry Pi. Raspberry Pi is notorious for its development boards used by engineering enthusiasts around the world. It is a dual-core, dual-architecture microcontroller [28]. The dual architecture allows the microcontroller to either run on RISC-V, or as an ARM processor. It operates on a frequency of 150MHz allowing for fast operations and computations. The RP2350B offers 48 GPIO pins, 8 analog inputs (pins directed towards an ADC), and 2 MB of internal flash memory [28]. With 520Kbytes of on-chip Static random-access memory (SRAM) it can run bulky programs. It supports a variety of peripherals including up to 2 UART, 2 x SPI controllers, 24 Pulse-Width Modulation (PWM), 1 USB 1.1 controller, and 12 peripheral Input/Output (PIO) state machines [28]. The RP2350B requires a voltage input of 2.7V-5.5V which routes to the internal voltage regulator within the chip. It also supports Serial Wire Debug (SWD) which is a two-pin protocol that allows debugging, pausing, and tracing through a serial interface. This requires fewer pins than a traditional JTAG and offers faster debugging speeds.

3.1.1.2 Table Comparison of MCUs

	ESP32-WROOM-MD	MSP430F6459	RP2350B
Cores	2	1	2
CPU Frequency	80MHz-240MHz	20MHz	150MHz
Wi-Fi Support (Natively)	Yes	No	No
Bluetooth Support (Natively)	Yes	No	No

Ram	448kB ROM, 520 kB of SRAM	512kB non-Volatile, 66 kB RAM	520kB of SRAM
Supports external Memory	Yes	No	Yes
GPIO Pins	38	74	48

Table 2 : MCU Comparison

3.1.1.3 MCU Selection

Due to the stronger CPU in terms of both cores and frequency, the SDP will utilize the ESP32-Wroom-MD. The dual cores operating at 240MHz will provide fast computing and operations. The 38 GPIO pins are enough due to multiple peripherals being connected to SPI, allowing for multiple peripherals to be connected without using too many GPIO pins. The native support for Bluetooth and Wi-Fi will help us allow the consumer to easily use our device through a wireless connection. The ESP32-Wroom-MD is also one of the most widely used MCUs for embedded enthusiasts, leading to lots of support and information online.

3.1.2 Motor Controls

To control the motors accurately within our printer, we must make important design considerations on the motors, motor drivers, and software considerations. All these elements come together to ensure proper motor controls are required to meet our requirements. To move the printing nozzle as needed, our software must control outputs to pins connected to the stepper motor drivers, which in return use those signals to control the motors properly.

3.1.2.1 Motor Technologies

This section sets out to research the technologies associated with motors. What types of motors are out there, and what is the best option for our purpose. There are three main types of motors that will be researched: servo motors, stepper motors, and DC motors. Each type of motor is a common technology used to take advantage of electricity to mechanically move a motor.

3.1.2.1.a Servo Motors

Servo motors also known as “servos” for short is a type of rotary actuator that is traditionally used for angular or linear position applications. Servos have built in ICs that change the voltage across a potentiometer that is used to control the output of a DC motor. This motor is typically attached to a set of gears that adjust the torque and rotations per minute to control the output shaft. Servos are precise due to the nature of using feedback of the potentiometer that is linked to an IC that creates great precision. The use of the DC motor also provides lots of torque which is required for large loads.

3.1.2.1.b Stepper Motors

Stepper motors offer discrete steps to control movement. This is great for precise applications due to easily being able to move a distance relative to the multiples of these discrete steps. Stepper motors are often classified by their size and offer a specific number of degrees of rotation per step. They are often open-loop systems as they do not require feedback to ensure and check motor rotation. Stepper motors are precise but are worse relatively under large loads. They don't provide enough torque, while maintaining a fast-operating speed. Stepper Motors should be used for precise small applications.

3.1.2.1.c DC Motors

DC motors use direct current (hints in the name DC) to produce mechanical force. They utilize two permanent magnets with electromagnets set on a rotating element. By pushing current into the electromagnets, the DC motor can create a repelling force due to the polarization of the magnetic field. This repelling force causes the spinning movement of the armature. DC motors are the most fundamental of the motors research as they are the most basic. The concepts used for DC motors are also implemented into both servo and stepper motors to create movement. DC motors allow for easy speed control by adjusting the voltage used to supply the current to the commutator. One downside of DC motors is that they lack precision relative to other motor types.

3.1.2.1.d Table Comparison of Motors

	DC Motors	Stepper Motors	Servo Motors
Precision	Low	High	High
Torque	High	Low	High
Control Type	Open-loop	Open-loop	Closed-loop
Cost	Low	Low	High

Table 3 : Motor Type Comparison

3.1.2.1.e Summary and Motor Selection

Due to the importance of precision within the SPD's requirements. The Stepper Motor will be the motor type of choice for the project. Stepper Motors are the standard for applications within 3D printing and CNC machining due to their precision and relatively low cost. By utilizing multiples of steps, the software will

properly be able to calculate the steps required to move the printer in each direction once calibrated.

3.1.2.2 Stepper Motors Selection

The National Electrical Manufacturers Association (Nema) specifies standards and specifications for classes of stepper motors. This allows a numerical representation of each motor based upon the dimensions of the face plate. For instance, a Nema 17 has a 1.7-inch square faceplate while a Nema 23 has a 2.3-inch square faceplate. The larger the motor the higher the power supported, resulting in more mechanical torque. Due to the similarities, and only difference in size and power supported. The SPD will utilize the Nema 17's as the stepper motor of choice. The Nema 17's are the most common among 3D printing enthusiasts and commercial products alike.

3.1.2.3 Stepper Motor Drivers

Due to the nature of stepper motors requiring a large voltage (typically 8 Volts – 35 Volts) with a nominal current of at least 1 Amp, hooking up a microcontroller directly to a high volt line is not recommended. Thus, an IC or a circuit is required for the microcontroller to control the board indirectly. It is an industry standard to use specialty boards designed specifically for stepper motors, these are the “stepper motor drivers”. These specialty boards control specific ICs and other components designed specifically to control stepper motors. It is common for these boards to provide additional functionality such as micro stepping, sleep pins, current limits, reset pins, heat distribution, and other functionalities that are helpful for motor controls.

In this section we will look at a few of the most popular options to compare. Each board will have a brief description as well as pros and cons to ensure we are selecting the most viable driver board. Each of these boards is named based on the IC used, note that there are some different versions of each board that have some small changes.

3.1.2.3.a A4988

The Allegro A4988 is a stepper motor driver that has been prominent in industry since 2019. It is a bipolar stepping motor, allowing it to use all the coils within the stepper motor itself for efficient driving [29]. This board offers three micro stepping resolution pins, allowing for 5 micro stepping resolutions: 1, 1/2, 1/4, 1/8, and 1/16 [29]. It operates the motor itself using an input voltage of 8 Volts – 35 Volts and can be rated for up to 2 Amps with proper cooling (most manufactures include a heatsink for the IC itself). It includes a potentiometer on board allowing in order to set a maximum current. It also includes an over-temperature thermal shutdown, under-voltage lockout, and crossover-current protection to increase reliability. This motor movement is controlled by two-pins, using a STEP + DIR controls in order to ensure proper movement.

3.1.2.3.b DRV8825

The Texas Instruments' DRV8825 is another bipolar stepper motor that was released in January of 2021. It operates the stepper motor by using an input motor power supply of 8.2 Volts – 45 Volts [30]. It supports six micro stepping resolutions from 1 to 1/32 of a step, allowing for more precision. The MCU controls the micro stepping resolution through 3 pins connected to the DRV8825. It contains a 4-layer 2 oz copper PCB for improved heat dissipation [30]. It has a potentiometer used to set the maximum current and supports a maximum current of 2.2 Amps (assuming proper cooling). It also provides over-temperature thermal shutdown, over-current shutdown, and under-voltage lockout.

3.1.2.3.c TMC2225

The Analog Devices TMC2225 is a newer stepper motor driver that is classified as a “ultra-silent” motor driver. It is specifically optimized to be one of the quietest motor drivers on the market. It supports micro stepping of up to 1/256 by utilizing a technology called “MicroPlyer Interpolation”. Which interpolates the time between two step impulses on the Step Pin and breaks it apart into 256 equal micro steps. The TMC2225 operates on a voltage input of 4.75V-36V, and a logic high voltage of 3.3V-5V. It supports a max current of 2A per coil.

3.1.2.3.d Table Comparison of Stepper Motor Drivers

	A4988	DRV8825	TMC2225
MicroStepping Resolution	1/16	1/32	1/256
GPIO Pins Required (Minimum configuration)	2 (Step + Dir)	2 (Step + Dir)	2 (Step + Dir)
Voltage Input (DC)	8V-35V	8.2V-45V	4.75V-36V
Logic Voltage Level (High)	3V-5.5V	2.2V-5.25V	3.3V-5V
Max Current	2A	2.2A	2A
Price per single unit (For the IC, not full board)	\$4.25	\$5.73	\$5.61

Table 4: Stepper Motor Driver Comparison

3.1.3 User Controls / Displays

For the embedded system in our project, we will need some way to control the printer, select which PCB file to print solder on, and overall control the machine. Using a display is a great way to interact and control the printer. There are a multitude of considerations to look over when choosing a display.

3.1.3.1 Resistive vs Capacitive Touch Screen Displays

Resistive and capacitive touch screens are commonly used in embedded projects. The touch screens both have their own advantages and disadvantages. Capacitive touch screens allow for multiple touches to be registered simultaneously where only one touch can be registered for a resistive touch screen [31]. Resistive touch screens are cheaper to make than capacitive ones so resistive ones have a lower cost [31]. Capacitive touch screens have a glass outer layer whereas resistive touch screens have an outer layer consisting of a plastic film [31]. A glass layer is going to last longer than a plastic layer as the glass layer is more resistant to scratches and fogging up after being used for a long time [31]. Resistive touch screens can be used without direct conductive contact because they register touches based on force whereas a capacitive one needs conductive contact like a stylus or finger (depending on the model) for a touch to be registered [31].

For the uses of the project, a capacitive touch screen is going to be better than a resistive touch screen when comparing the trade-offs. The users are most likely to not be wearing something to prevent the use of a stylus or their finger from manipulating the touch screen. Also, even though the cost of the resistive touch screen is less, the price increase for the capacitive touch screen is worth it because the glass outer layer of the capacitive touch screen will allow for longer use without having to replace the screen and the multi-touch capability of a capacitive touch screen allows for more unique and seamless use of the touch screen.

3.1.3.2 Display Controllers

The display controller is the most crucial part of the display. It is the middleman for the microcontroller, to control each individual pixel on the display. There are many display controllers that can be considered for the project, but that large list can be shortened by the previous two sections reviewing where capacitive and resistive touch displays are compared, and where the communication protocols SPI and I2C are compared. Also, it is important to pick the right display controller as it also determines other properties of the display module like the size of the display that can be used. Also, for deciding on a display module overall, I will just be choosing by display controller because manufacturers just list displays by display controller name and the dimensions of the display. The top options that need to be compared are the ST7789, the ST7735, the HX8357, the ILI9488, and the ILI9341.

3.1.3.2a ST7789

The ST7789 has a pixel resolution of 240 x 320 pixels [32]. The display is two inches. It supports a color depth of eighteen bits which is 262,144 unique colors [32]. The display also has an SPI interface [32]. It has a voltage regulator, so the input voltage is supported for the range between 3.3 and 5 volts [32]. On the display, there is a slot for a microSD card reader to hold images that can be displayed [32].

3.1.3.2b ST7735R

The ST7735R is a 1.8-inch display with a pixel resolution of 128 x 160 pixels [33]. It can interface with a microcontroller using SPI [33]. Similarly to the ST7789, it has a color depth of eighteen bits. It also has a voltage regulator that can support an input of 3.3 to 5 volts, and a microSD card reader [33].

3.1.3.2c HX8357

The HX8357 has a bigger display than the last two at 3.5 inches [34]. It has a pixel resolution of 320 x 480 pixels and a color depth of eighteen bits [34]. The input voltage for the display is compatible with 3.3 volts or 5 volts [34]. The display also interfaces with SPI and has a microSD card reader [34].

3.1.3.2d ILI9488

The ILI9488 is similar to the HX8357. It has a 3.5-inch display with a pixel resolution of 320 x 480 pixels [35]. The color depth of the display is sixteen bits [35]. The interface it uses for communication is SPI [35]. It can receive an input voltage ranging from 3.3 volts to 5 volts [35]. It does differ from the HX8357 by having an SD card slot instead of a microSD card slot [35].

3.1.3.2e ILI9341

The ILI9341 meets a nice middle ground between the previously mentioned displays. It has a 3.2-inch display with a pixel resolution of 240 x 320 pixels [36]. The color depth is sixteen bits [36]. It also does interface with SPI and accepts an input voltage between 3.3 volts and 5 volts [36]. The display, similarly to the ILI9488, has an SD card slot [36].

3.1.3.2f Display Controllers Comparison Table

	ST7789	ST7735R	HX8357	ILI9488	ILI9341
Interface(s) to microcontroller	SPI	SPI	SPI	SPI	SPI
Pixel Resolution (pixels x pixels)	240 x 320	128 x 160	320 x 480	320 x 480	240 x 320
Color Depth (bits)	18	18	18	16	16
Screen Size (inches)	2	1.8	3.5	3.5	3.2
microSD card reader	Yes	Yes	Yes	No	No
SD card reader	No	No	No	Yes	Yes

Table 5 : Display Controllers Comparison Table

3.1.3.2g Summary

Between the displays researched and, in the table, our team is going with the ILI9341. The ILI9341 uses SPI which will blend well with the other devices needed to be connected to the ESP32 and overall help simplify our design. It boasts a touch screen which can be used by a finger or stylus. The color depth is great enough to display various colors which can be needed for the project. Also based on the resolution to screen size, 240 x 320 and 3.2 inches, the screen is just the right size, not too small or too big, for having menus on it and for the text and buttons to be readable.

3.1.4 Optical Sub-System

3.1.4.1 CMOS Sensors for Passive Stereoscopy

There are many kinds of Complementary Metal Oxide Sensors (CMOS) out on the market, at an affordable price. For this reason, the stereo vision system will utilize a CMOS sensor. Most CMOS sensors, under \$100, utilize a camera serial interface connector or an SPI interface. This works considering our options for computers. The sensor that is selected must have enough resolution to be able to adequately image a 7.07 mm radius.

3.1.4.1.a Raspberry Pi HQ Sensor

The Raspberry Pi HQ sensor features a 1/2.3", Sony IMX447, CMOS sensor with a pixel count of 12.3 MP. Each pixel being 1.55 micron by 1.55 micron. The sensor features a 22-pin CSI-2 connector and was designed to be used with a Raspberry Pi computer board. It has a price of around \$50 and the sensor has a diagonal length of 7.9 mm. The sensor comes with an integrated IR filter and can be easily integrated with a lens tube using the thread that is attached to the sensor. The Raspberry Pi HQ sensor comes with only one sensor, no lens attached. The sensor outputs RAW12/10/8 file types. The SNR and dynamic range of the sensor are not given and are just labeled as "high" in the specification sheet. The sensor includes a variety of features such as defect pixel correction or dual sensor synchronization operation. [37]

3.1.4.1.b Arducam OV2640

The Arducam OV2640 is a compact sensor module and lens assembly that features a sensor of 1600 x 1200 pixels (2 MP) with each pixel being a square with a length of 2.2 microns. The sensor in the Arducam OV2640 was produced by OmniVision. The sensor has a diagonal length of 4.5 mm and a price of \$10-\$15. The sensor is connected using a standard 15-pin CSI connector making it compatible with platforms like the ESP32. The sensor already comes with a lens installed which would need to be removed to attach other optics. The sensor itself is small and does not offer the best resolution. The sensor requires 1.3V DC and consumes around 140 mW at its most intensive operational mode. The sensor has a dynamic range of 50 dB and a signal-to-noise ratio of 40 dB. At its maximum resolution, the sensor has a maximum image transfer rate of 15 FPS.

3.1.4.1.c Arducam IMX230

The Arducam IMX230 features a Sony IMX230 CMOS sensor that has 5344 x 4016 pixels (21 MP) with each pixel being 1.12 micron by 1.12 micron. The sensor has a diagonal length of 8.4 mm and can output 24 FPS at the largest resolution and 30 FPS at a resolution of 4K. The sensor comes with an integrated infrared filter.

This sensor module runs from \$80-\$90. It features a CSI-2 connector strip making it compatible with platforms like the Raspberry Pi. The sensor output format is RAW10. The data sheet does not include specific values for the dynamic range and the signal-to-noise ratio, they are simply labeled as “high”. The sensor includes features to improve image quality, like advanced noise reduction and defect pixel correction, like the IMX 447. [38]

3.1.4.1.d Arducam 5MP OV5642 SPI Sensor

The Arducam 5MP SPI sensor is a sensor based on an OV5642 CMOS sensor, by OmniVision, with an array size of 2592 x 1944 pixels with each pixel being a square of 1.4 μm . This corresponds to an image area of 3.673 mm x 2.738 mm. The sensor features SPI connectivity and a 60-degree field of view lens that can be detached. This sensor can be used with any platform like Arduino, Raspberry Pi, and ESP. If the platform can communicate with the sensor using SPI, it should be compatible with the sensor. The sensor module is \$40, and it outputs a JPEG RGB RAW8 image file type. The sensor requires a power supply of 3.3V~5V. The image transfer rate depends on the resolution of the images. At 5 MP this sensor has a maximum image transfer rate of 15 FPS. At 1080p, it has a maximum image transfer rate of 30 FPS. The sensor itself comes with corrective focusing technology that can help extend the depth of field in an image. The sensor has a dynamic range of 68 dB and a signal-to-noise ratio of 36 dB. The sensor also features OmniBSI pixels of the OmniVision that are optimized for low-light performance. [39]

3.1.4.1.e Table comparison of sensors for passive stereoscopy

	Raspberry Pi HQ Sensor IMX 477	Arducam OV2640	Arducam IMX 230	Arducam 5MP OV5642 SPI Sensor
Price	\$50	\$10-\$15	\$80-\$90	\$40
Removable Lens	Yes	Yes	Yes	Yes
Sensor size (pixels)	4056 x 3040	1600 x 1200	5472 x 3648	2592x1944
Sensor size (MP)	12.3 MP	2 MP	21 MP	5 MP
Pixel Size	1.55 μm x 1.55 μm	1.75 μm x 1.75 μm	1.12 μm (w) x 1.12 μm (h)	1.4 μm x 1.4 μm
Sensor size (mm)	7.44 mm x 5.96 mm	4.6 mm x 3.4 mm	7.216 mm x 5.497 mm	3.67 mm x 2.73 mm
Diagonal Length	7.9 mm	4.5 mm	7.487 mm	4.57 mm

Dynamic Range	“High”	50 dB	“High”	68 dB
SNR	“High”	40 dB	“High”	36 dB
Power Supply	Analog: 2.8 V Digital: 1.05 V I/O: 1.8 V	Core: 1.3V Analog: 2.5~3.0V I/O: 1.7V to 3.3V	3.3V DC (standard to MIPI)	5V/390mA
Connector	CSI-2 interface	CSI-2 interface	2-Lane MIPI CSI-2 interface	SPI interface

Table 6: Sensors for Passive Stereoscopy Comparison

3.1.4.1.f Sensor Summary + Selection for Passive Stereoscopy

There are a variety of sensors on the market ranging from price and capability. For our applications, we have selected the Arducam 5MP OV5642 SPI sensor has 5MP and provides detailed images. The OV5642 sensor comes with built-in image processing to ensure quality images, even in low-light scenarios. It also comes with the proprietary TrueFocus image signal processor of OmniVision to sensor interface uses SPI, which is useful as we do not need a second separate microcontroller to connect the two assembled camera modules. We can connect sensors to our ESP 32 board.

3.1.4.2 Lenses for Passive Stereoscopy

The following paragraphs will discuss options for lenses for the stereo vision camera modules. When selecting a lens for our individual camera modules, we must consider what our requirements are. We need a biconvex lens. The lens should not be too small in diameter as this would make it difficult to work with when assembling the camera modules, but it should not be too large where we lose depth of field in the image. An adjustable aperture would allow us to restrict the diameter of the lens to achieve a lower NA and as a result higher depth of field. However, including an adjustable aperture may create additional disparity in the quality of the images so if we are considering adding an aperture, it must be fixed. The focal length of the lens selected must not be higher than 50 mm to ensure that the entire optical system can function when installed on the solder paste dispenser. We will be considering lenses with a focal length of 40 mm. This allows us to maintain a higher depth of field while ensuring the modules will be short enough to fit. The lens we select must have sufficient transmission and minimal aberrations.

3.1.4.2.a Thorlabs LB1378-A (Bi-Convex N-BK7 Lens)

The Thorlabs LB1378-A is a bi-convex, spherical lens made of SCHOTT N-BK7 glass. The glass has a refractive index (n) of 1.517 at 588 nm. The diameter of the lens is 12.7 mm (1/2 inch) and it has a focal length of 40 mm. The lens is coated with a 350 nm – 700 nm anti-reflection coating ensuring high transmission. The lens has a transmission of around 90%. The finished surface quality of the lens is 40-20 scratch-dig, so it has a good surface finish. A mounted Thorlabs LB1378-A-ML lens costs \$52.28. For analysis, figures below, created using Ansys ZEMAX OpticStudio, are shown. These figures contain information about the minimum spot size, the Seidel coefficients and a general layout of the optical system with the lens. [40]

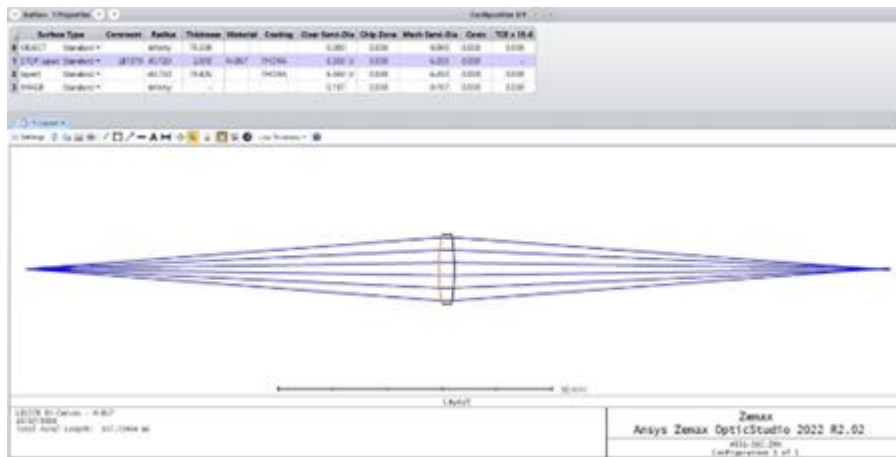


Figure 7: Thorlabs LB1378-A optical configuration in Ansys ZEMAX OpticStudio.

Title: LB1378 Bi-Convex - N-BK7
Date: 10/17/2024

Wavelength	:	0.5876 μ m
Chief Ray Slope, Object Space	:	0.0000
Chief Ray Slope, Image Space	:	0.0000
Marginal Ray Slope, Object Space	:	0.0757
Marginal Ray Slope, Image Space	:	-0.0694
Petzval radius	:	Infinity
Optical Invariant	:	0.0000

Seidel Aberration Coefficients:

Surf	SPHA S1	COMA S2	ASTI S3	FCUR S4	DIST S5	CLA (CL)	CTR (CT)	
STO	0.019825	0.000000	0.000000	0.000000	0.000000	-0.006559	-0.000000	LB1378
2	0.017855	-0.000000	0.000000	0.000000	-0.000000	-0.006380	0.000000	
IPA	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	
TOT	0.037680	0.000000	0.000000	0.000000	0.000000	-0.012938	0.000000	

Figure 8: Seidel Coefficients for Thorlabs LB1378-A

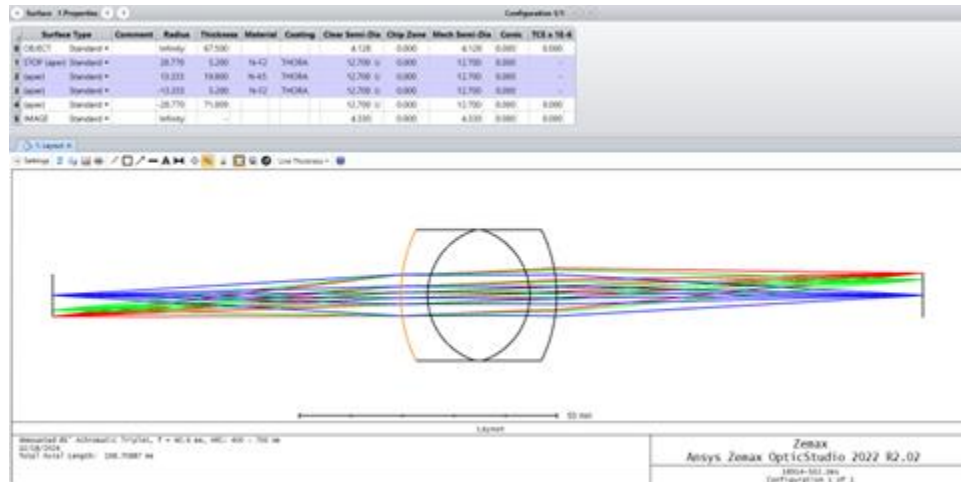


Figure 13: Thorlabs TRS254-040-A Optical Configuration in Ansys ZEMAX OpticStudio

Title: Unmounted Ø1" Achromatic Triplet, f = 40.6 mm, ARC: 400 - 700 nm
Date: 10/18/2024

Wavelength	:	0.5876 μm
Chief Ray Slope, Object Space	:	0.0612
Chief Ray Slope, Image Space	:	0.0434
Marginal Ray Slope, Object Space	:	0.0593
Marginal Ray Slope, Image Space	:	-0.0564
Petzval radius	:	-48.3720
Optical Invariant	:	0.2447

Seidel Aberration Coefficients:

Surf	SPHA S1	COMA S2	ASTI S3	FCUR S4	DIST S5	CLA (CL)	CTR (CT)
STO	0.010935	0.003373	0.001040	0.000796	0.000566	-0.008333	-0.002570
2	-0.008659	-0.001641	-0.000311	-0.000178	-0.000093	0.008315	0.001576
3	-0.008588	-0.001012	-0.000119	-0.000178	-0.000035	0.008345	0.000984
4	0.010613	-0.000024	0.000000	0.000796	-0.000002	-0.008332	0.000019
IMA	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
TOT	0.004301	0.000695	0.000510	0.001237	0.000437	-0.000005	0.000008

Figure 14: Seidel Coefficients for the Thorlabs TRS254-040-A

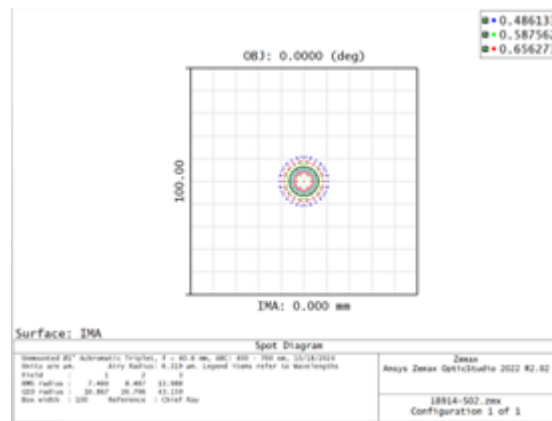


Figure 15: Standard Spot Size Diagram for the Thorlabs TRS254-040-A

3.1.4.2.c Analysis of Lens Options

All the 40 mm lens options were configured to achieve the same magnification. All simulated configurations have an acceptable length regarding the design requirements.

Seidel coefficients represent the magnitude of optical aberrations as a fraction of the wavelength of light used in a system. Aberration becomes significant and noticeable when the Seidel coefficients start to reach 0.25 or 0.5, a quarter or half of the wavelength of light in an optical system. For the Seidel coefficient values for spherical aberration at 587.6 nm, the LB1378 has a coefficient value of 0.0377, the TRH-040-A Hastings triplet has a coefficient value of 0.00367, and the TRS-040-A Steinheil triplet has a coefficient value of 0.00430. We see a significant improvement in reducing spherical aberrations using triplets rather than the singlet; However, overall, none of the lenses have significant aberrations.

The standard spot size diagram shows the focused spot size at the image plane and provides information like root-mean-squared (RMS) spot size and airy radius. To minimize blur in our image, it's important to reduce the RMS spot size so it is close to the airy radius. The LB1378, in its configuration, has an RMS spot size radius of 83.3 microns and an airy radius of 4.9 microns. The TRH-040-A Hastings triplet, in its configuration, has an RMS spot size radius of 8.4 microns and an airy radius of 6.5 microns. The TRS-040-A Steinheil triplet, in its configuration, has an RMS spot size radius of 7.5 microns and an airy radius of 6.3 microns. The triplet lenses offer much better optical performance than the singlet lens.

3.1.4.2d Table comparison of lenses for passive stereoscopy

	Thorlabs LB1378-ML	Thorlabs TRH-040-A-ML	Thorlabs TRS-040-A-ML
Price	\$52.28	\$111.38	\$117.31
Working Distance	40 mm	68.2 mm	68.2 mm
Focal Length	40 mm	40 mm	40 mm
Diameter	12.7 mm	25.4 mm	25.4 mm
Type	Singlet	Hastings triplet	Steinheil triplet

Table 7: Comparison of Lenses for Passive Stereoscopy

3.1.4.2.e Lens Summary + Selection for Passive Stereoscopy

There are a variety of lenses to choose from, each varying in price, performance, and characteristics. For maximizing performance and image quality, we have

chosen to select the 40 mm focal length Hastings cemented triplet lens. This lens is useful for our applications. The lens is optimized for infinite conjugate imaging, which is useful for magnification applications. The triplet also has excellent aberration compensation. In combination with an aperture, we should be able to achieve our depth of field.

3.1.5 Extruding Sub System

3.1.5.1 Solder Paste

Solder paste will be dispensed on all the PCB boards from the dispenser. There are different types of solder paste depending on a variety of parameters including alloy, flux, and size. For the best results then one of the solder paste types needs to be chosen to be used within the dispenser.

First and foremost, before solder paste is made, there is just solder powder made from an alloy. The most common alloys are SAC305 or eutectic. Eutectic is an alloy comprised of tin and lead. SAC305 is an alloy combination of tin, silver, and copper. Both eutectic and SAC305 consist mostly of tin because it has a relatively low melting point of five hundred-five Kelvin and in other terms two hundred thirty-one Celsius. Since lead is hazardous, eutectic alloys have been mainly pushed aside and SAC305 is mainly used in the surface mount technology industry. The copper in SAC305 helps lower the melting point of the alloy and the silver helps by adding extra mechanical strength to the alloy. Other metals that are included in other less commonly used alloys include nickel, indium, antimony, and bismuth. [43]

The next component of solder paste is the flux which helps turn the solder powder alloy into the paste that is well known. The flux is primarily used to clean the surface to solder on and allow the solder powder to have wetting which makes it spreadable and able to come out of a dispenser smoothly. There are three types of flux which are water-soluble flux, no-clean flux, and rosin-flux. [43]

Rosin-flux is a mildly aggressive cleaning agent and good for wetting. The rosin-flux does have a downside when it comes to cleaning the leftover residue after the soldering process. Special solvents need to be used to remove unwanted residue to prevent corrosion. [43]

Another type of flux is water-soluble flux. It is great for removing oxide layers which clean the surface to solder on and is a more aggressive cleaning agent than rosin-flux. Water-soluble flux is problematic because it does not burn off well which means it gets left behind on the PCB and all the flux needs to be removed to prevent corrosion. Corrosion can occur on the PCB if the leftover water-soluble

flux residue is left. An advantage over rosin-flux is that for the cleaning process, only water is needed to clean the water-soluble flux off. [43]

A flux that does not need excessive cleaning was the next development which brought no-clean flux. There was a trade-off made in the development to not need cleaning. No-clean flux does not clean the surface to the same level as water-soluble flux because it is not as aggressive as a cleaning agent. There are also combinations of no-clean flux and rosin-flux that need little cleaning and have a better cleaning agent than no-clean flux alone. [43]

The particle size is the last main component of solder paste. The particle sizes of each solder paste type are identified by the type number, which describes the particle size of the solder powder alloy. The range of types is one to eight with type one having the largest solder paste particle sizes to type eight which has the smallest particle sizes. IPC is the standard that determines the size to type for the solder powder particles. [43]

The process of using a spray to atomize molten solder powder and then sifting the particles in a series of meshes allows for the collection and organization of the different-sized solder powder particles for each solder paste type. The type number also refers to mesh size as well as the particle size. [43]

The most common type sizes to be used are type three and type four, which range with particle sizes from twenty-five to forty-five microns and twenty to thirty-eight microns respectively, as they are the most applicable size for most applications. As electronics have become smaller and smaller over time, the types with smaller particle sizes have increased in popularity. The project will best support tubes of solder paste of type three and type four based on the precision of the stepper motors that will be used and have been chosen previously. [43]

3.1.5.1a Solder Paste Type Comparison Table

IPC Type	Minimum Aperture Size (millimeter)	Powder Size (microns)
1	30	75-150
2	15	45-75
3	9	25-45
4	7.5	20-38
5	5	15-25
6	3	5-15
7	2.5	2-11
8	2	2-8

Table 8: Solder Paste Type Comparison Table [43]

3.1.5.2 Nozzles

One of the most important systems for this solder paste dispenser is the nozzle that the team must use in order to actually dispense solder paste. There are multiple nozzles capable of extruding fluids like solder paste such as tapered nozzles, blunt-end needles, tapered needles, micro-precision nozzles, multi-orifice nozzles, and SMT nozzles. Of course, not all of these nozzle/needle types are capable of delivering the high precision this project requires; it also depends on the positioning and the size of the tip of the extruder [44].

One thing to keep in mind is the team is trying to achieve an SMD package size of 0603(imperial) / 1608(metric) as the basic goal. The advanced goal would be to achieve a more precise SMD package size such as 0402(imperial) / 1005(metric). The stretch goal entails reaching smaller SMD package sizes such as

0201(imperial) / 0603(metric) to 01005(imperial) / 0402(metric). The different types of nozzles that will be elaborated on must be able to at least come in a suitable size to achieve the basic goal requirement.

In addition, different gauges allow for different flow rates. To help understand flow rates per gauge of solder, we can reference the flow rates in catheters (commonly used for IV fluids in the medical industry). As previously discussed, solder paste has different viscosity and materials, so it will not accurately represent the data shown in the table below for IV flow rates. In addition, the data in the table refers to constant flow. The solder paste will not be dispensed constantly, rather it will be dripped for miniscule periods of time [45].

Gauge Size	Outer Diameter (OD) (mm)	Length (mm)	Flow Rate (mL/min)
14 Gauge (G)	2.1 mm	45 mm	240 mL/min
16 Gauge (G)	1.8 mm	45 mm	180 mL/min
18 Gauge (G)	1.3 mm	32 mm	90 mL/min
20 Gauge (G)	1.1 mm	32 mm	60 mL/min
22 Gauge (G)	0.9 mm	25 mm	36 mL/min
24 Gauge (G)	0.7 mm	19 mm	20 mL/min
26 Gauge (G)	0.6 mm	19 mm	13 mL/min

Table 9: Nozzle Diameter and Flow Rate Relationship

Although this next table does not specify flow rates, TEquipment also provides good reference for outer diameters and inner diameters of their 12.7 mm length general purpose tips (resembling blunt-end needles). TEquipment sells all types of electronics tools like soldering irons, dispensing equipment, multimeters, and much more. The table below is another reference as to the dimensions of these needles/nozzles used for dispensing fluids [46].

Gauge	Inner Diameter (ID) (mm/inches)	Outer Diameter (OD) (mm/inches)
14G	1.54 mm / 0.060"	1.83 mm / 0.072"
15G	1.36 mm / 0.053"	1.65 mm / 0.065"
18G	0.84 mm / 0.033"	1.27 mm / 0.050"
20G	0.61 mm / 0.024"	0.91 mm / 0.036"
21G	0.51 mm / 0.020"	0.82 mm / 0.032"
22G	0.41 mm / 0.016"	0.72 mm / 0.028"
23G	0.33 mm / 0.013"	0.65 mm / 0.025"
25G	0.25 mm / 0.010"	0.52mm / 0.020"
27G	0.20 mm / 0.008"	0.42 mm / 0.016"
30G	0.15 mm / 0.006"	0.31 mm / 0.012"

Table 10: Inner and Outer Diameters of Different Nozzle Gauges

As can be seen in the two tables above, the higher the gauge, the smaller the diameter. With a smaller diameter comes a lower flow rate. The difference between the inner and outer diameters represents the thickness of the needle. Both of the tables above are examples of the relationship between needle thickness, diameter, and flow rates. It is difficult to fully match the specifications provided in the table with the requirements for this project, these are simply used for reference purposes to get a better understanding of how nozzles and needles are measured and sold. Based off this information, there are several different types of nozzles and models that will be considered for use.

3.1.5.2.a Nozzle Types

Starting off with the tapered nozzle, it is a gradually narrowing nozzle with a cut off end (it does not narrow down to a sharp point). These are also called tapered tip needles. These types of nozzles are good for a controlled and constant flow of fluid. If used for activities like welding, it would be more flow oriented than precision oriented. However, if utilized for lower viscosity fluids there are higher gauge tapered nozzles that can do the job. For example, there are 30G precision tapered nozzles that are used for “bio-printing” in the medical field. Alongside this, the tapered tips dispensing needles are also used for solder paste and sold on DigiKey. Some happen to be plastic tips and others are stainless-steel tips [47].

A blunt-end needle is different as it has a much thinner shaft and tip compared to the tapered nozzle. They also come in various high gauges and typically seem to have a plastic base with a stainless-steel needle. Similar to the tapered nozzles, the application for higher gauges of this type of needle seem to be for the medical industry. However, there are some blunt-end needles that TEquipment sells which are used for soldering and dispensing purposes [46].

The micro-precision nozzle is similar to the tapered tip but is much shorter in length. This conical nozzle has thinner walls which results in the liquid not sticking to the end as much when it is dispensed. This improves flow rate and accuracy of the fluid being dispensed. These are based on the micro-precision nozzles sold by Subrex, which can dispense down to about 50 μm , which is around the same as 21G [48].

The multiple orifice nozzle includes several openings allowing for fluids to flow from multiple directions. These may prove to be useful for larger applications such as cleaning, fire extinguishing, cooling; or it could possibly be used in a situation when vast amounts of solder paste will be placed. Most multi-orifice nozzles online seem to be made of brass. Typically, these are used in hydraulics, which the team might not utilize in their final design as it is used more for mass spraying than it is for

precision. Some can be purchased that spray at a 100-500 μm range, meaning it is similar to a 21G to 30G range [49].

Despite not being primarily used for solder paste dispensing, it is worth mentioning surface mount technology (SMT) nozzles made by Neoden USA, who make pick and place machines, reflow ovens, stencil printers, and other PCB handling equipment. The SMT nozzles are used for pick and place machines, such as the CN040, and are recommended for 0402 components. Although it is not advised, the CN040 nozzle seems to resemble a 21 gauge or 22 gauge needle based on the TEquipment table above. That is because the external diameter is 0.8mm and the internal diameter is 0.4mm capable of placing down 0402 components. However, it will not be considered for dispensing solder [50].

3.1.5.2.a Nozzle Types Comparison Table

	Tapered Nozzle/Needle	Blunt-end Needle	Micro- precision Nozzle	Multi- Orifice Nozzle	SMT Nozzle
Application	Solder / Medical	Solder / Medical	Solder / Medical	Industrial	Pick & Place
Gauge	High	High	High	High	High
Price	Cheap	Cheap	Moderate	Expensive	Cheap

Table 11: Nozzle Type Comparison Table

The tapered nozzle/needle and blunt-end needle types appear to be the most versatile and easiest to use out of the options researched for this application. However, the tapered nozzle will be selected to use for this project. The tapered nozzle allows for a higher flow rate than the blunt-end needle does. That is because the tapered nozzle gradually decreases its diameter, allowing for more of a higher cross-sectional surface area than the blunt-end needle. The blunt-end needle remains at a constant very thin diameter, requiring more power to push all of the fluid out. Not only are tapered nozzles typically used for soldering purposes, but there are high gauge nozzles of this type being sold in mass quantities for a relatively cheaper price than the other options. Besides the blunt-end needle and the micro-precision nozzles, the others are unrelated to solder paste dispensing. This makes the tapered nozzle the best option for this application.

3.1.5.3 Methods for Dispensing

There are a few methods worth mentioning regarding how the team plans on dispensing solder. Now that the nozzle/needle types have been researched, there are two primary methods that the team is considering implementing into their design. One method is a pneumatic system that utilizes air pressure, the second method is a stepper motor-driven system.

Pneumatic systems utilize compressed air to initiate motion in mechanical parts. These systems include filtering, regulating, and lubricating processes in order to ensure there is no dust or other materials that could get in the way. They typically have control over multi-directional air flow by using a set of valves such as a center-exhaust valve. In addition, they require some form of rotary system that allows the air to be driven in the pneumatic device. For example, electric motors and nozzles are used to achieve said air compression. Finally, a pneumatic system needs a medium to deliver compressed air; this is typically some type of flexible tube that is then connected to whatever requires said air pressure [51].

A stepper motor-driven system is an alternative that utilizes electric stepper motors to act like a pump in a dispenser. There are two main ways that stepper motors can be used for pumping purposes: a peristaltic pump and a rotating screw pump. The peristaltic pump works by rotating a stepper motor that has a wheel with two lumps attached to its shaft. The lumps firmly press down on the fluid containing tube, preventing the fluid from flowing. As the first lump presses down on the tube, it creates a vacuum that pumps more liquid into the tube from the source. The second lump then presses down on the tube causing that newly entered fluid to be pushed out through the output. This process repeats allowing more fluid to enter from one side and be forced out of the other side. Since the peristaltic pump does not require any openings on the tube, it has a good seal to prevent leakage [52].

On the other hand, a rotating screw pump attaches a screw to the shaft of a stepper motor. The other end of the screw has a flat or pointed cylinder that matches the inner diameter of the tube, attempting to create a perfect seal to prevent fluid leakage. The fluid to be dispensed will be placed on the other side of this cylinder. As the stepper motor turns on and rotates, the screw will rotate, screwing further towards the end tip of the nozzle, thus pushing fluid out. These are similar to piston pumps that might also utilize motors to perform dispensing. Both a small peristaltic pump and a rotating screw pump can be easily controlled via a stepper motor driver and a microcontroller.

There are other relevant methods that are simply variants of the ones just described. Some of these alternatives may be more mechanical, too complex for the scope of this project, or just entirely irrelevant. For example, gravity feed dispensing will not be useful for this project as there needs to be control over the flow at all times. Electrostatic dispensing is completely unrelated to dispensing solder paste. Other types of valve dispensing are relevant, but more complex versions of the aforementioned systems.

3.1.5.3.a Methods of Dispensing Comparison Table

	Pneumatic	Peristaltic	Rotating Screw
Precision	High	Moderate	Moderate
Noise	High	Low	Low
Power Consumption	High	Low	Low
Applications	Solder / Medical	Solder	Solder
Price	Moderate	Cheap	Cheap

Table 12: Methods of Dispensing Comparison Table

All three of these main methods can prove to be useful in their own ways. Pneumatic systems can provide higher precision since the exact PSI can be set by the user. However, pneumatic systems can also be a noisier and more power-consuming method since they either utilize a built-in or an external air compressor. When it comes to powering up the solder paste dispenser as a whole, the team might have to omit powering the pneumatic system from the selected power supply. This would result in needing to connect the pneumatic system to the house separately from the solder paste dispenser.

The stepper motor-driven systems can still provide reliable control over paste flow while avoiding noise and power issues. The stepper motors will have to be powered and controlled by a stepper motor driver, similar to the ones used for coordinate plane navigation. This will require less power than the pneumatic system, but it must be tested and configured in order to figure out how much power is required to reach the desired flow rate.

3.1.5.3.b Conclusion

The tapered nozzle is going to be the nozzle of choice of at least 25G or above; this should ensure an SMD package size of 0603 (imperial). The team is heavily favoring the idea of a stepper-motor driven system since it provides moderate levels of precision, is not a noisy system, is cheap, and has already been used for solder paste dispensing. The power consumption of a pneumatic system is too high, often requiring one or two extra external systems to provide air pressure for dispensing. When it comes to narrowing it down, the peristaltic pump might offer slightly higher precision than the rotating screw will.

3.1.6 Power Sub System

3.1.6.1 Power Supply Types

A power supply is necessary to provide power for all systems within the Solder Paste Dispenser. For example, power must be distributed to the custom PCB which houses the microcontroller, stepper motor drivers, stepper motors, switches, touchscreen display, stereoscopy system, and dispenser nozzle. Designing a power supply from the ground-up requires extensive knowledge on rectification, filtering, regulation, and safety methods. Instead, it would be more cost-effective and time-efficient to research and adapt the project's design to a commercial off-the-shelf (COTS) power supply.

The current scope of the project requires power to be delivered to the ESP32, two OV5642 cameras, four stepper motor drivers (and stepper motors), and the ILI9341 touchscreen display. The power specifications and ratings of the Ender-3 V2 Neo are very similar to what the team plans on using. The ESP32 has maximum ratings of 3.6V at 1,100mA which results in 3.960W. One individual OV5642 camera normally operates at 5V and 390mA, resulting in 1.95W consumption. Two of these cameras would be 5V at 780mA resulting in a 3.9W consumption. Each of the stepper motor drivers can handle 35V at 2A consuming a total of 70W. Considering there will be four (three for navigation and one for dispensing) that roughly means that the drivers will require 35V at 8A consuming 280W. The stepper motors have the highest power consumption out of any other subsystem in this project. However, not all 35V will be used. Based on the testing shown in the mini demo video, the team was able to rotate the stepper motor shaft using only 14V at 2A. If this is consistent across all 4 of the stepper motors, that will reduce power consumption from 280W down to 112W. The ILI9341 touchscreen display consumes less than 100mW of power while operating at 3.3V. The touchscreen will not play a big factor in the type of power supply required.

Now that the project's specifications have been covered, it can be seen that at most the dispenser will consume roughly 288W. The highest tested voltage being used on the stepper motors is 14V and roughly the total current consumption is 9.9A. The power supply should be able to comfortably offer this and be able to surpass this in the event the team decides to utilize extra peripherals from their stretch goals. Before looking into the specifications and power ratings of the Ender-3, there are many different types of power supplies. Alongside the multiple power supply types, there are various terms and definitions to cover before reading a PSU datasheet. The two main types of power supplies are linear power supplies and switched mode power supplies.

3.1.6.1.a Linear Power Supplies

Linear power supplies convert AC voltage into a steady DC output voltage with relatively low ripple and noise. Below is a figure provided by Rohde & Schwarz to describe the design principles of the linear power supply. There are two stages of circuits seen in the image below, the primary circuitry is the AC input stage seen on the left. The transformer separates the two stages, stepping down the AC input voltage and isolating them from each other. The beginning of the secondary stage rectifies the AC into DC through the rectifier. The actuator acts like a switch to provide control over the output. This is managed by the analog control (output) amplifier, which when controlled by the reference voltage, acts like a buffer [90]. As the buffer detects a difference between the positive and negative terminals, it tries to match the values seen in the terminals and turns on the actuator, thus providing output voltage from the rectifier output. In addition, two buffer capacitors are placed to help decrease ripple and increase stabilization of the DC signal.

Generally, this is how a linear power supply operates. For example, Matsusada Precision provides a diagram showcasing a very similar way to achieve the operation of a linear power supply. Similar to Rohde & Schwarz where the circuit is split up into an input stage and an output stage, the AC input goes right into a step-down transformer and then into a rectifier. The “smooth” capacitor performs the same function as the buffer capacitors from the previous design, where it is used to reduce ripples and keep a constant DC signal. Despite this design providing less details, the series regulator here is basically the combination of the voltage reference, actuator, and analog control amplifier from the previous design [53]. According to Monolithic Power Systems (MPS), voltage regulators use four main components: pass transistors, error amplifiers, voltage references, and a resistor feedback network [54]. This in combination with the low pass filter (which adds a capacitor between the positive and negative terminals of the output) matches very closely to the above design.

Linear power supplies require a transformer, rectifier, buffer, and filter. The smoothing or buffer capacitor and the stabilizing circuit ensures that the positive sinusoidal waves coming out of the rectifier are leveled out to keep it at a stable DC. However, circuits like this require cooling methods or large heat sinks as this linear power supply generates heat.

3.1.6.1.b Switched-Mode Power Supply

Switching over to switched-mode power supplies, one of the main differences is the order of circuitry when compared to linear power supplies. Using another circuit diagram provided by Rohde & Schwarz, it can be seen that the first step is to rectify the input AC voltage into DC. This voltage is then smoothened out by that capacitor

connected to the ground and any high-frequency voltage is clipped. The switching transistor is meant to emulate AC by switching on and off very rapidly, as the voltage is then fed into a high-frequency transformer. After it is stepped down using the transformer, a rectifier and low pass filter is used to stabilize and level off the DC voltage [55]. In addition, a control component is placed to regulate the switching transistor by changing its duty cycle (a percentage representing the period that a signal is high/low).

Similarly, the MPS shows switched-mode power supplies to start off with a rectifier circuit, followed by a smoothing capacitor. The stepped down voltage through the high frequency transformer is induced and controlled by the switching device and control circuit. Then, it is rectified again and filtered to become DC output voltage [53]. The switching device acts as a “chopper” which is a type of DC-to-DC converter used to step up/down DC power [56]. It changes fixed DC power to variable DC power with a series of high frequency pulses.

Switched-mode power supplies basically utilize this DC-to-DC conversion strategy to emulate AC with DC pulses; this process is typically referred to as pulse width modulation (PWM), producing analog signals with DC signals and using it to control a signal [57]. They require two rectifications (one at the input and another after the transformer), a switching transistor, a high-frequency transformer, a control circuit, and a low pass filter.

3.1.6.1.c Comparison between Linear and Switched-Mode

When comparing the two main types of power supplies, there are a few key differences worth noting. Switched-mode power supplies produce more noise over linear power supplies because of the high-frequency switching transistor. The switched-mode power supply is smaller in size than the linear power supply because the high-frequency transformer is smaller than typical low-frequency transformers (as a result it also weighs less). Due to the switching transistor, the switched-mode power supply is more efficient because it is constantly being turned on and off. Meanwhile, the linear power supply is always on and wastes more energy via heat resulting in lower efficiency. Linear power supplies respond faster to changes in the load because they respond using their voltage regulator rather than the switched-mode’s entire control circuit. When it comes to the cost of either one, it depends on the application and how much power is going to be used. For example, linear power supplies can typically be cheaper in low-power applications, but switched-mode can be cheaper in high-power applications [53].

3.1.6.1.d Other Types of Power Supplies

Despite linear and switched-mode being the most common types of power supplies found in electronics, there are various other forms of power supplies use for several other applications. For example, there are uninterruptible power supplies (UPS), battery power supplies, programmable power supplies, power over ethernet (PoE), solar power supplies, etc. [58]. However, these power supplies are not necessarily useful for the application of this project. An uninterruptible power supply provides power in emergency situations when the main power source fails or is interrupted. Although losing power during a long dispensing session might be worrisome, it certainly is not an emergency that is worth the price of a UPS. A battery power supply would not be of much use considering the Solder Paste Dispenser must remain on for lengthy periods of time and is not portable, justifying the lack of necessity. Programmable power supplies like the ones seen in circuits laboratories are simply too vague and versatile for this application. The programmable power supply in and of itself is its own consumer product that is not specifically used to power machines; it is more for powering and testing systems. Power over ethernet is simply delivering power through ethernet cables into a device. The main issue with this is the low power rating and current being delivered within the milliamp range. Finally, the use of solar power is just extremely unnecessary and unfeasible for a Solder Paste Dispenser that is meant to sit inside of a room-temperature or cooled room.

Now that some of the other types of power supplies have been listed off and described, the topic returns to linear versus switched-mode power supplies. It is evident that the switched-mode power supply has a greater complexity than that of the linear power supply. For the purpose of this project, it appears that a switched-mode power supply is the better option. It is smaller and more efficient than the linear power supply and noise is not too big of a factor for this application.

3.1.6.2 Datasheet Common Specifications and Conditions

Now that the power supply types have been narrowed down, there are multiple conditions and parameters to consider when choosing a power supply and reading its datasheet. Using the Mean Well LRS-350-24 datasheet as an example (further elaborated on later), there are several output parameters such as DC voltage, rated current, current range, rated power, ripple & noise, voltage adjustment range, voltage tolerance, line and load regulation, setup time, rise time, and holdup time. DC voltage and rated power are both basic output voltage and output power specifications. The rated current is the maximum continuous DC current that the PSU can output, and the current range describes the minimum and maximum current values that it provides. Ripple (measured in millivolts peak-to-peak) is often seen as a periodic AC component at the DC output, meanwhile noise consists of various frequency spikes in the voltage of the output. The combination of both of these tests is referred to as periodic and random deviations (PARD). The voltage

adjustment range in this case applies to the terminal on the switched-mode power supplies that can be oftentimes adjusted via a screwdriver to change the range of output voltage while maintaining other output characteristics. Line and load regulation are shown as percentages that describe the PSU's ability to keep its specified output voltage when a change occurs in the input line voltage or in the load. Voltage tolerance is the combined tolerance of both of these test specifications. Setup time is the time it takes for the PSU to become functional and begin outputting voltage. Rise time is the time it takes for the PSU's output to reach a steady state, which is usually right after the setup time finishes. Finally, holdup time is the amount of time it takes the PSU to recover back to a continuous output voltage after loss of input power. All three of the past specifications regarding time usually depend on the load [59].

Moving on to the input specifications, there is voltage range, frequency range, efficiency, AC current, inrush current, and leakage current. Voltage range simply describes the acceptable range of input voltage that the PSU operates within (considering this is a switched-mode power supply it can sometimes be either an AC or DC voltage range since they act like DC-to-DC converters). The frequency range is the range of acceptable input frequencies that the PSU operates in (many times it will house 50 Hz or 60 Hz). Efficiency describes the ratio of output power to input power for the PSU (many times the efficiency in switched-mode power supplies is significantly higher than that of linear power supplies). AC current is the allowed input current from an AC source into the power supply. Inrush current is the current that occurs right after the input voltage is applied to the power supply. Finally, leakage current is a safety concern for power supplies as it is current that flows from the input neutral wire or input live wire to the metal grounding casing [59].

There are various protections in place for these power supplies such as overload (overcurrent), overvoltage, over temperature, overpower, short circuit, and under voltage protection. Overload protection protects the circuit from high levels of current by latching off or entering a recovery mode. Similarly, short circuit protection prevents a surge of current from occurring caused by a short circuit in the power supply. Overpower protection also attempts to stop the power supply from allowing more current flow than its power rating allows for. The main difference is that overpower protection is placed on the primary side where a rectifier circuit is, while overcurrent protection is placed on the secondary side. Overvoltage protection is meant to prevent a surge of voltage from affecting the rest of the internal circuitry, meanwhile, undervoltage protection is meant to prevent power loss and some components from being damaged. In addition to these protection features, power supplies also require a method of cooling down. Some manufacturers choose to cool down their power supplies via convection while others need forced cooling using a DC fan [59].

There are also environmental factors that affect the efficiency and operation of power supplies such as working temperature, working humidity, storage temperature, storage humidity, temperature coefficient, vibration, and over voltage category. Working temperature and humidity simply state what the acceptable temperature range and humidity levels are for the device to operate in. The same goes for storage temperature and humidity where it describes the environment that the device should be stored in when it is not operating. Temperature coefficient refers to the percentage change in the output voltage per 1°C change in temperature. The vibration specification is the power supply's resistance to vibration, showcasing its mechanical strength. Finally, the overvoltage category describes the maximum overvoltage that the power supply can handle if the power supply fails. The category ranges from I to IV, each one inversely indicating the minimum number of protective devices in place between the device and the substation transformer that delivers the power [59].

Alongside all of the specifications regarding voltage, current, power, temperature, and more, there are also safety standards that many power supplies are required to follow. Some of the safety specifications include safety standards, withstand voltage, isolation resistance, and electromagnetic compatibility (EMC). Safety standards are often set by organizations such as IEEE and specific ones may be referenced to show that a power supply abides by said standards. The withstand voltage is a rating for the insulation and voltage that a power supply can handle without failing between two points such as the input and output. Isolation resistance is similar in the sense that it describes the resistance between two points on the power supply like the input and output. EMC Emission and Immunity determine the power supply's intended environment of operation based on the emissions it releases and the immunity it has towards electromagnetic fields (EMF) or radiation. There are also a few extra things to consider like the "mean time between failures" (MTBF) which represents the length of time a PSU should operate reliably and "mean time to failure" (MTTF) which is a more accurate measurement of how long it would actually take for it to fail. Alongside this, datasheets typically include size dimensions, and weight of the device [59].

The specifications listed were just some of the many that can be found in a power supply's datasheet. Some of these are more important factors to consider than others when it comes to selecting the part that is suitable for this project. There are other specifications that were not listed but still might show up depending on the manufacturer/designer.

3.1.6.3 COTS Power Supplies

To determine the power supply needed for all of these components, we can first take a look at the required power supply specifications in the Creality Ender-3 V2

Neo. This is the model of the Ender 3 that the team plans on modifying into a solder paste dispenser. The Ender-3 V2 Neo plugs into an AC wall socket via a wall plug, its rated input voltage is 100-120V AC (6.8A), 200-240V AC (3.4A) at 50/60 Hz [60]. Its rated output voltage is 24V (~14.6A) and its rated power is 350 W. This information can be found on the official Creality website. The Ender-3 V2 Neo's specifications and power/voltage ratings match the ratings of the majority of the 3D printers within the Ender Series of Creality (with the few exceptions being the Ender-3 (270W), Ender-3 Pro (270W), Ender-6 (360W), Ender-5 Pro (270W), and Ender-5 Plus (550W)). The Ender-3 V2 Neo has a sleeker design compared to other Ender Series 3D printers by hiding away its power supply underneath the printing bed. For example, the Ender-3, Ender-3 Pro, and Ender-3 Max all have an exterior power supply sticking outside of the device [61].

3.1.6.3.a Creality CMS 350-24

There are a few power supplies that match the power ratings for the Ender-3 V2 Neo such as the CMS 350-24 Switch Power Supply. The CMS 350-24 is a Creality-made power supply unit (PSU) that supplies 24V DC at 14.5A (in the USA) with an input of 100-120/200-240VAC (6.8/3.4A) at 50/60Hz. This model has one output voltage regulation terminal, three positive output terminals, three negative output terminals, one ground wire terminal, one neutral line terminal, and one live wire terminal. The three positive and three negative output terminals are what provide the 24V DC for the device. This PSU is meant to provide power to the ground wire, neutral line, and live wire terminals are meant to be the input of the PSU from an AC power source (wall outlet).

The CMS-350-24 also provides safety features such as short-circuit protection, overvoltage protection, overload protection, and over-temperature protection. Other notable features include its operating temperature range of -20°C ~ +70°C. Its rated power is 350.4W with an output voltage of 24V. The PSU has size dimensions of 215 x 115 x 30 mm (8.46 x 4.53 x 1.18 inches) and a weight of 0.63 kg (~1.39 lbs) [62].

3.1.6.3.b Mean Well LRS-350-24

The Ender-3 V2 3D Printer of Creality uses a similarly rated power supply by Mean Well called the LRS-350-24. The Mean Well LRS-350 Series is a set of 350W Switching Power Supply with single outputs that are rated for various voltage/current outputs/inputs. The LRS-350-24 is the 24V output model which delivers a current range anywhere from 0 - 14.6A. It is rated for exactly 350.4W and has a maximum ripple and noise of 150mVp-p. The input voltage range begins at around 90 ~ 132VAC or 180 ~ 264VAC at the frequency range of around 47 ~

63Hz with an efficiency of 88%. The input stage AC current allows for 6.8A to flow at 115VAC meanwhile 3.4A at 230VAC.

Similar to the CMS 350-24, it has short circuit protection, overload protection, over-voltage protection, and over-temperature protection. In the datasheet, overload is considered to be 110 ~ 140% of the rated output power, in this case being 350W [59]. Upon reaching this overload condition, the power supply will enter “Hiccup mode” to ensure that the condition is removed. Hiccup mode is a safety feature on switch-mode power supplies that basically turns off the power converter when an overload is recognized, restarts the converter, and checks again for overload [63]. In general, overloads could be due to low loads resulting in overcurrent or overvoltage. Moving on to the over-voltage protection, the LRS-350-24 considers the range 28.8 ~ 33.6V to be over-voltage. Depending on the severity of this condition being met, the power supply could enter into Hiccup mode or Latch off mode. Finally, the over-temperature protection conditions are similar in the sense that if the working temperature of -25°C ~ +70°C is surpassed, then the Hiccup mode or even the Latch off mode will activate. It shares the same terminal types as the CMS-350 with one output voltage regulation terminal, three positive output terminals, three negative output terminals, one ground wire terminal, one neutral line terminal, and one live wire terminal. On top of those features, it is also capable of enduring an input surge of 300V AC for about 5 seconds. Similar to the CMS-350-24, the LRS-350-24's size dimensions are 215 x 115 x 30mm (8.46 x 4.53 x 1.18 inches) and has a packaging weight of 0.76 kg (~1.68 lbs).

3.1.6.3.c Mean Well S35024

The next PSU that will be looked at is the Mean Well S35024. This power supply has not been used in an Ender-3 3D printer but bears very similar specifications to the voltage and power ratings of the Ender-3 V2 Neo. For starters, it is another single-output switching power supply and a part of Mean Well's S-350 Series of PSUs. The S-350-24 is the 24V output model rated for output current range from 0 – 14.6A and rated power of 350.4W. Just like the LRS-350-24, it has a maximum ripple and noise voltage of 150mVp-p. The input voltage range is 90 ~ 132VAC or 180 ~ 264VAC with a frequency range of 47 ~ 63Hz and an efficiency of 81%. The input stage AC current is lower than that of the LRS-350 series, allowing for 6.5A to flow at 115VAC meanwhile 4A at 230VAC.

One of the main differences between the two series is that the S-350 series lacks over-temperature protection and cannot withstand a high surge input. Despite the lack of over-temperature protection, the working temperature range is -10°C ~ +60°C. As a result, the S-350 series has a lower cost, and power supply than the LRS-350 series. The S-350 still has overload protection which is labeled as 105 ~ 135% of the rated output power. However, it does not have hiccup mode nor latch-

off mode; instead, it constantly monitors and limits current levels until there is no longer overcurrent. The over-voltage protection defines overvoltage to be 27.6 ~ 32.4V with hiccup mode available. The S35024 has ten terminals: one for voltage adjustment, three for positive output voltage, three for negative output voltage, one for the ground wire, one for the neutral line, and one for the live wire. The size dimensions are 215 x 115 x 50 mm (8.46 x 4.53 x 1.97 inches) with a packaging weight of 1.07 kg (~2.36 lbs) [64].

3.1.6.3.d Mean Well UHP-350-24

Another similar power supply from Mean Well is the UHP-350-24. This is another switching power supply, but instead it is part of the UHP-350 series. The UHP-350-24 supplies 24V DC, 14.6A, and is rated as 350.4W. The maximum ripple and noise voltage is 240mVp-p, which is considerably higher than that of the previous PSUs. The input voltage range is 90 ~ 264VAC with frequency range of 47 ~ 63Hz and efficiency of 94%. The AC input current is 4A at 115VAC and 2A at 230VAC. The primary difference from the previous two Mean Well PSUs includes the UHP-350-24 having an active power factor correction (PFC) circuit, which prevents phase delays between the voltage and current. This function reduces current distortion and adjusts the power factor to have a higher ratio of real power to apparent power [65].

The UHP-350-24 also has short circuit protection and brings back the ability to withstand a 300VAC surge input for 5 seconds, similar to the LRS-350-24. Its overload protection categorizes overload to be 110 ~ 140% of the rated output power and it uses hiccup mode to fix the condition. Overvoltage protection will shut down the output voltage when it reaches the range of 26.4 ~ 31.2V (it will not automatically turn back on, the user must manually re-power). This PSU also has over-temperature protection where it shuts down output voltage when it surpasses the working temperature range of -30°C ~ +70°C (power supply will recover on its own upon temperature decreasing). On top of having the largest range for working temperature, the UHP-350-24 does not utilize DC fans for cooling but rather it just uses convection; this results in a less noisy operation. Finally, it has a significantly slimmer design with size dimensions of 220 x 62 x 31 mm (8.66 x 2.44 x 1.22 inches) and a packaging weight of 0.68kg (~1.50 lbs) [66].

3.1.6.3.e Delta PMT-24V350W1AK

Stepping away from Mean Well PSUs, there is a panel mount, and switch power supply made by Delta called the PMT-24V350W1AK. This power supply is part of the PMT series and supplies the usual 24V DC, 14.6A, and is rated for 350.4W. The output can be adjusted anywhere from 20.0V DC to 26.4V DC. Since this is a switching power supply, it can be selected for it to either input 100-120V AC or 200-

240V AC (with a range of 90-132V AC or 180-264V AC single phase). The nominal input frequency sits between 50Hz to 60Hz with a frequency range of 47Hz to 63Hz. The AC input current at 115V AC is 7A meanwhile at 230V AC it is 4A with an efficiency of 87.0% at 230V AC and 100% load. It has a ripple and noise voltage of less than 150mVpp.

In addition to these electrical characteristics, it has overvoltage protection, overload (overcurrent) protection, over-temperature protection, short circuit protection, shock protection, and an internal fuse. Overvoltage for this PSU is defined as above 32.4V (it will automatically shut off if reaches higher) and any voltages below this threshold are considered safety extra low voltage (SELV). The device can also handle up to 25A of rated load current, anymore beyond that will make the PSU enter Hiccup mode and will automatically turn back on once it reaches below the threshold again. The same Hiccup mode safety features will be used when the power supply reaches a temperature above its operating temperature of -10°C ~ +70°C. The short circuit protection has hiccup mode, and the shock protection is done by having a connection to Earth. Like most other power supplies discussed earlier, it is air-cooled via a DC fan. The size dimensions for this device are 215 x 115 x 50 mm (8.46 x 4.53 x 1.97 inches) and has a unit weight of 0.82 kg (~1.81 lbs) [67].

3.1.6.3.f Cosel WMA350H-24

The final switching power supply that will be looked at is the Cosel WMA350H-24. As part of the WM series, it is a single output switching power supply that provides a maximum output wattage of 350.4W with 24V and 14.6A. It has an input voltage range from either 85-132V AC or 170-264V AC (single phase) with an input AC current of 6A at 115V or 3.3A at 230V. It operates at 50/60Hz and has a frequency range of 47-63Hz. The device has an efficiency of 87% when running at 115V AC and 88% when running at 230V AC. With a 100% load, the power supply has a ripple noise of up to 150mVp-p.

It only has overcurrent and overvoltage protection. The PSU can operate up to 105% of its rating, and the overcurrent protection seems to implement a hiccup mode that allows the device to recover automatically. The overvoltage protection kicks in somewhere between the voltage range of 27.6V to 33.6V, but it is not clear whether it is hiccup or latch. Its operating temperature range is from -20°C ~ +70°C using an internal fan for forced cooling. The dimensions for this device are 115 x 30 x 215 mm (4.53 x 1.18 x 8.46 inches) and weighs 800g (~1.76 lbs) [68].

3.1.6.3.g RS PRO 233-6892

The final switching power supply being considered is the RS PRO Embedded Switch Mode Power Supply Model 233-6892. This power supply is meant to be used for medical and industrial purposes, but it matches the requirements needed for our device. For example, it has an input voltage range from 90-264V AC with a frequency range of 47-63 Hz. At 115V AC it takes 4A and at 230V AC it takes 2A. It outputs 24V DC at 14.6A for a rated power of 350W with an efficiency of 93%. It also has 150mVpp maximum ripple and noise voltage.

It has a few protections in place such as overvoltage, which it defines as being above 30V. When the over 30V condition is met, the PSU will turn off the output voltage and will have to be manually re-powered for it to recover. Overcurrent protection allows it to self-recover when the output current goes beyond 110% of its rated output current. Finally, short circuit protection also has a self-recover mode. The power supply has no overtemperature protection, but it is fan-cooled with an operating temperature is -40°C ~ +70°C. Finally, it has size dimensions of 130 x 86 x 35 mm (5.12 x 3.34 x 1.38 inches) and weighs 430g (~0.95 lbs) [69].

3.1.6.3.h Power Supply Unit Comparison

Now that plenty of power supplies have been covered, it is obvious that many of them have striking similarities with only a few minute differences. For example, each of these has the same ten-terminal layout: one voltage adjustment/regulation terminal, three positive DC output terminals, three negative DC output terminals, one AC ground wire terminal, one AC neutral line terminal, and one AC live wire terminal. Due to the specifications of the Ender-3 V2 Neo, all the aforementioned power supplies have a general range of input AC voltages that allow house 100-120V AC or 200-240V AC at 50/60 Hz. Each of them outputs 24V at 14.6A which gives them a 350.4W power rating. Many of them have some assortment of protections for either overvoltage, overload, overcurrent, overtemperature, or short circuits. The areas that they each mainly differ in are the number of protections they have, the operating temperatures, the efficiency of the power supplies, leakage or ripple/noise, sizes, and weights. Some of the more important factors include efficiency, protection, and size of the PSU. Ideally, the power supply wastes the least amount of power possible, has the most circuit protections in place for safety reasons, and is as compact as possible to fit within the frame of the Ender-3 V2 Neo's housing space. Below is a table comparing the various specifications of each of these power supplies.

3.1.6.3.i Table Comparison Between Power Supply Units

In the table below, there are some key things to keep in mind. Short-circuit is labeled as "SC," overvoltage is labeled as "OV," overload is labeled as "OL," over current is labeled as "OC," and overtemperature is labeled as "OT."

	CMS 350-24	LRS-350-24	S35024	UHP-350-24	PMT-24V350W1AK	WMA350H-24	233-6892
Manufacturer	Creality	Mean Well	Mean Well	Mean Well	Delta	Cosel	RS PRO
Type of PSU	Switched-Mode	Switched-Mode	Switched-Mode	Switched-Mode	Switched-Mode	Switched-Mode	Switched-Mode
Rated Output Voltage	24V	24V	24V	24V	24V	24V	24V
Rated Output Current	14.6A	14.6A	14.6A	14.6A	14.6A	14.6A	14.6A
Rated Power	350.4W	350.4W	350.4W	350.4W	350.4W	350.4W	350W
Input Voltage	100-120/200-240VAC	90-132/180-264VAC	90-132/180-264VAC	90-264VAC or 127-370VDC	90-132/180-264VAC	85-132/170-264VAC	90-264VAC or 127-370VDC
Input Current	6.8A/115VAC or 3.4A/230VAC	6.8A/115VAC or 3.4A/230VAC	6.5A/115VAC or 4A/230VAC	4A/115VAC or 2A/230VAC	7A/115VAC or 4A/230VAC	6A/115VAC or 3.3A/230VAC	4A/115VAC or 2A/230VAC
Efficiency	NA	88%	81%	94%	87%	87%	93%
Frequency	50/60 Hz	47-63Hz	47-63Hz	47-63Hz	47-63Hz	47-63Hz	47-63Hz
Ripple and Noise	NA	150mVpp	150mVpp	240mVpp	150mVpp	150mVpp	150mVpp
Leakage Current	NA	<2mA/240VAC	<3.5mA/240VAC	<0.75mA/240VAC	<3.5mA/240VAC	<0.3mA/115V or <0.5mA/240VAC	<0.1mA
Operating Temperature	-20°C ~ +70°C	-25°C ~ +70°C	-10°C ~ +60°C	-30°C ~ +70°C	-10°C ~ +70°C	-20°C ~ +70°C	-40°C ~ +70°C
Cooling	Fan	Fan	Fan	Convection	Fan	Fan	Fan

MTBF	NA	328.6K hrs (25°C)	234.3K hrs (25°C)	285K hrs (25°C)	700K hrs (35°C)	NA	>300 K hrs (25°C)
Protec tions	SC, OV, OL, OT	OL, OV, OT	OL, OV	OL, OV, OT	OV, OL, OT, SC	OC, OV	OV, OC, SC
Metho d of Protec tion	NA	Hiccup Mode	Current limiting, Hiccup	Hiccup, Shut down	Latch, Hiccup	NA	Shut down, Const ant curre nt
Safety Class (Over Voltag e Cat.)	NA	III	NA	NA	II	NA	I
Dimen sions (mm)	215x115x30	215x115x30	215x115x50	220x62x31	215x115x50	115x30x215	130x86x35
Weight (kg)	0.63	0.76	1.07	0.68	0.82	0.8	0.43
Cost	\$31.67 (Creali ty)	\$38.11 (DigiKey)	Obsolet e	\$69.31 (MeanWell)	\$74.98 (DigiKey)	\$75.88 (DigiKey)	\$133.84 (eeze e)

Table 13: Table Comparison Between Power Supply Units

3.1.6.3.j Power Supply Selection

Before settling on the final power supply selection, it is important to also note how these power supplies will be powered on. Considering each of these power supplies have screw on terminals, they will all require a three-prong power cord with an exposed live, neutral, and ground wires on the opposite end. In order to ensure the best connection, the exposed wires should be crimped with either a ring connector or a fork connector around it. The connector would then be screwed into place at the input terminals of the power supply. This should secure a good connection between the power cord and the power supply. A similar strategy would occur when securing connections between the output of the power supply and the input of the devices receiving power.

With all of that information provided, comparisons can be made to finalize the power supply selection. Based on the table above, if the selection were to be made based on efficiency the two best options would be the Mean Well UHP-350-24 and the RS PRO 233-6892. If the comparison was based on the number of protections, the best options would be the Creality CMS 350-24 and the Delta PMT-24V350W1AK. If it were based on dimensions, the smallest PSUs would be the RS PRO and the UHP-350-24. Finally, if it was based on cost, the two cheapest options are the CMS 350-24 and the LRS-350-24. There are several other factors that the selection could be based on; however, it seems as if the best option is not the one that is the greatest at one or two factors, but the most versatile power supply that is good enough with all factors.

In that case, the LRS-350-24 is the most versatile. It receives and provides the required input and output. It has an efficiency of 88%, which compared to the rest is average. It has the typical ripple and noise voltage with a down-the-middle leakage current. It has a good operating temperature and is cooled via an internal fan. The LRS has an MTBF higher than most of the other aforementioned power supplies. It has three important protections that use hiccup mode, those being overload, overvoltage, and overtemperature. It is not the biggest power supply nor is it the smallest one, just like it is not the heaviest nor the lightest. Finally, it is the second cheapest option out of the seven discussed. With that being said, it covers all the bases and provides enough protection to satisfy the requirements. In addition, the LRS-350-24 was also used in the Ender-3 V2 Neo, proving that it is capable of supplying enough power to it and works reliably.

If more information was provided for the Creality CMS 350-24 then it would possibly outshine the other options, but the website lacked a lot of necessary specifications. The UHP-350-24, PMT-24V350W1AK, WMA350H-24, and the RS PRO are significantly more expensive than the LRS. The efficiency of the UHP-350-24 and especially the RS PRO does not justify the steep price. In addition, the S35024 is obsolete and is not being manufactured or sold anymore. The WMA350H-24 has a small number of protections and does not specify its MTBF on the datasheet. The PMT24V350W1AK is a good rival to the LRS, however, despite its great MTBF, it is also double the price of the LRS and slightly bigger. The ideal size dimensions of the power supply are the ones specified in the Ender-3 V2 Neo. All of these reasons contribute to the finalized selection that the LRS-350-24 is the power supply of choice for the Solder Paste Dispenser.

3.2 Software

3.2.1 Integrated Development Environment (IDE) Selection

3.2.1.a IDE Overview

The Software Environment encompasses the process of developing, compiling, and deploying the code for the project. Having an efficient environment allows for a reduction in the time associated with deploying and debugging. There are a variety of features to look for in a debugger, flashing tool, serial monitor, extensions, error checking, auto-complete (IntelliSense), and performance testing.

The two main environments that will be researched are PlatformIO, an extension for Visual Studio Code, and the Arduino IDE. Both of these IDEs are focused on embedded programming and provide the functionality required to build an efficient project. Embedded programming requires additional tools in order to flash MCUs and to be able to use a JTAG for debugging.

3.2.1.b Arduino IDE 2

The official Arduino IDE 2 is a free IDE developed specifically for embedded programming. The Arduino IDE is based upon creating “sketches”, or projects in which users can import libraries and create and flash code onto an embedded device. It offers a cloud service to save your sketches remotely. Arduino IDE 2 comes with all the necessary tools required for embedded programming including upload, verify, and debug. The verifying tools allow developers to see if their code is buildable, and to verify there are no errors while compiling the code. The upload tool will build the source code and upload it to the specified board. It does this through a serial port connected to the MCU itself (or through a JTAG). The debugger is to be used with a JTAG device to allow developers to read specific registers on the MCU for debugging purposes.

The Arduino IDE also offers a library management tool. This tool provides developers with a quick and easy way to import open-source libraries from a vast database. These libraries include functionality for a variety of peripherals that can be controlled by MCUs. Everything from camera modules, stepper motors, touchscreens, and more can easily be imported from the IDE’s user interface (UI) directly. This allows for ease of use in including libraries into the sketch files to be implemented.

The Arduino IDE also comes with the Arduino Command Line Interface (CLI) tools. This enables developers to have the required functionality through CLI to build and upload their sketches. It has features for library management through the CLI itself. It offers all functionalities through the CLI to replace almost all features of the UI of the IDE itself, allowing other text editors to be used.

3.2.1.c PlatformIO Extension

The PlatformIO IDE is a Visual Studio Code extension that provides the functionality for embedded software development. Visual Studio Code (VS Code) is a text editor released by Microsoft with the intention of having a “blank slate” for developers to create their own personalized development environment. It has a rich set of extensions available to allow VS Code to perform a wide range of software-related tasks.

The PlatformIO IDE is a very common VS Code extension among embedded engineers. With 40+ platforms supported, 20+ frameworks, and 1,500 boards natively supported, this IDE allows developers to create projects for just about any system. It comes with tools to build, upload, debug, test, clean, and a serial monitor. The build is similar to Arduino IDE’s verify tool; it is also the compiler to build the project to verify there are no build errors. The upload tool will build and upload the project through a serial port that is connected to the MCU.

PlatformIO allows for easy configuration and changes to projects targeted framework and board. These configurations for PlatformIO lie within a “platformio.ini” file. This allows configurations for the framework, target board, platform, library dependencies, serial port monitor speeds, and more. This INI file gives PlatformIO instructions on how to build the project itself to ensure it is properly built for your specific MCU. When changing MCU, a developer can simply change the targeted board, and then re-build and upload the project. It also comes with a UI for configuring your project. This UI includes a library management tool and configuration to target a specific board. This helps developers who are new to PlatformIO quickly and easily get a project up and running. PlatformIO also has a range of tools created for commercial development. It includes a setup for unit testing to allow specific tests to be written. With an easy-to-use implementation, developers can quickly write unit tests and check their test coverage with the click of a button.

One major benefit of using PlatformIO is the access to all other VS Code extensions. VS Code has a rich marketplace for extensions that can be used alongside PlatformIO. Git extensions for version control can provide graphical interfaces to help manage branches and the repository. Official Microsoft C/C++ IntelliSense offers the most robust IntelliSense on the market, downloaded by over 72 million developers. This marketplace for VS Code allows developers to install extensions to save crucial time during development.

3.2.1.d Table Comparison Between IDEs

	PlatformIO	Arduino IDE 2
Boards Supported	1,500+	50+

Frameworks Supported	20+	1
Platforms Supported	40+	1
Build Tool	Yes	Yes
Upload Tool	Yes	Yes
Debugger Tool	Yes	Yes
Library Manager	Yes	Yes
Extensions	All VS Code extensions	No
CLI Tools	Yes	Yes

Table 14: Table Comparison Between IDEs

3.2.1.e IDE Selection

PlatformIO the Visual Studio extension will be the IDE of choice for the SPD project. The marketplace of Visual Studio Code extensions allows for lots of customizability to help make development more efficient. It also covers all of the features that the Arduino IDE has in a more customizable environment. It offers all needed tools in order for us to program, compile, flash, and debug our MCU and project.

3.2.2 Software Communication Protocols

3.2.2.1 SPI vs I2C

SPI (Serial Peripheral Interface) and I2C (Inter-Integrated Circuit) are used to allow a display to communicate with a microcontroller. Both of these communication protocols have their benefits and drawbacks.

I2C makes use of two pins, a serial data pin and a serial clock pin, to connect the microcontroller to the display and the display will be given a unique address [70]. The unique address is used so that devices connected to the I2C bus can identify if they are the ones being communicated with by the microcontroller. So, if more than one device needs to be connected over I2C then the devices will connect to the same two pins, and each will be given a unique address for themselves. The advantage here for I2C is that only two pins are needed in this simplistic design when connecting any number of devices to the bus [70]. Needing only two pins for I2C is an advantage because it frees up more pins on the microcontroller for other purposes and makes adding on more devices using the same protocol relatively easy to accomplish. The disadvantage of I2C is that it works in half-duplex which means lower speeds [71]. In half-duplex, information cannot be sent both ways simultaneously [71]. The microcontroller would have to send data to the display, then afterward the display could finally send information back to the microcontroller.

SPI uses four pins which are the MISO (Master In, Slave Out) pin, the MOSI (Master Out, Slave In) pin, the serial clock pin, and the chip select pin. The MISO pin allows one-way data transfers from the display to the microcontroller, and the MOSI pin is the opposite as it allows one-way data transfer from the microcontroller to the display. The serial clock keeps both devices that are connected synchronized, and the chip select pin signals if data can be transferred between the MISO and MOSI pins. If another device is to be added there are two ways to go about it. The first way is to make each device connected to the microcontroller use the same pins except each gets an individual chip select pin, so then the microcontroller will determine which device is being communicated with. The second way is that the devices and microcontroller are connected in a daisy chain with the MISO and MOSI pins, and they all share the same chip select pin and serial clock pin. The disadvantage of SPI is the extra pins needed for communication because it takes up more resources for the microcontroller [71]. The SPI protocol's advantage though is that the separate one-way data pins, MISO and MOSI, mean that it is full-duplex [71]. With full-duplex, the device and the microcontroller can communicate with each other simultaneously over the MISO and MOSI pins.

I2C works great for devices that are simple and do not require high speeds. When considering the device that will be used in the project is a display, SPI is going to be the better choice over I2C. After all, it is faster with a full-duplex design which gives speeds at ten megabits per second or more whereas I2C is limited to the usual four hundred kilobits per second or at the high end five megabits per second in Ultra-Fast mode because it runs in half-duplex [71]. The faster speeds from SPI will allow the display to refresh quicker and be much more responsive, giving users a better experience when interacting with the printer. With the high speeds of SPI, there is the downside that more pins will be used but that is a trade-off that needs to be made to give the users a user-friendly interface.

3.2.2.1.a SPI and I2C Comparison Table

	SPI	I2C
Pins Need (for one connection)	4	2
Bandwidth (kbps)	10000	400
Half-Duplex	Yes	Yes
Full-Duplex	Yes	No

Table 15: SPI and I2C Comparison Table

3.2.3 External Libraries

3.2.3.1 Stepper Motor Control Libraries

One benefit of using the Arduino framework with our microcontroller is the access to a large quantity of open-source libraries. Many libraries are developed by individuals and teams and are published to be imported into projects. Many of these libraries provide a stepper motor class that allows us to initialize our GPIO pins accurately, and to control the output to those pins as needed to move the motors.

There are many design considerations to look at when selecting a library. This includes access to documentation, ease of use, functionality, and reliability. When selecting a library, we want to have access to the documentation required to efficiently write the code needed to perform the functions required.

3.2.3.1.a Stepper by Arduino

This is the official Arduino Stepper Library. This library provides a single parent class containing three main methods (besides the constructors). These three methods are `setSpeed`, `step`, and `stepMotor` [72]. The constructor allows for the initialization of both two and four-pin motor drivers. Allowing for control of a large variety of boards. `Set Speed` allows the rotation per minute (RPM) to be set for the motor. Both the `stepMotor` and `Step` functions move the motor forward or backward a specific number of steps.

This library being the official Arduino library provides some credibility. It also has a document page on the Arduino website itself including some documentation on each method [72]. However, not all methods are covered in this site. The source code has great comments making it easy to follow and intuitively understand. However, this library is limited in functionality. It provides only the most basic methods to be used. Calibration and code would need to be written to calculate the distance moved per rotation.

3.2.3.1.b StepperDriver by Laurentiu Badea

This is a commonly used library for stepper motor drivers with 4,700+ downloads on Platform IO [73]. It offers driver-specific classes that are derived from the same parent class for basic stepper motor usage. It provides controls for two-pin motors that use STEP+DIR pins to control the motors. It also has some native support for Micro Stepping pins. It does provide some documentation however, it is limited to a single readme on GitHub as well as some example files showing separate use cases.

It provides a variety of methods such as `move`, `rotate`, `setSpeed`, `startRotate`, `calcStepPulse`, and more [74]. Its main movement is based per step, which will

require some calibration in order to get the right amount of steps/mm, in order to guarantee we can move a set distance within the margin of error from our requirements.

This library overall provides a large variety of functionality. As well as specific classes for the A4988, DRV8834, and more [74]. This allows for full control of all pins that are needed to connect to the Driver itself.

3.2.3.1.c Design a Library Ourselves

An alternative approach is to develop a custom library or set of classes tailored specifically to our requirements. This provides maximum configurability, allowing us to design functions that precisely meet our needs. For instance, we can implement movement functions that accept the required distances, enabling us to directly translate values from Gerber files and efficiently move between surface-mount devices (SMDs). Additionally, a custom library would enable better integration of motor control, allowing us to synchronize multiple motors to position the nozzle accurately during operation.

However, the downside to creating a custom library is the significant time investment required for development and debugging. While it offers the highest degree of flexibility, this approach may delay progress compared to using an existing open-source library, which provides readily available functionality and minimizes the effort required for initial implementation.

3.2.3.1.d Table Comparison Between Stepper Motor Libraries Available

	Stepper By Arduino	StepperDriver By Badea	Custom Library
Driver Specific Classes	No	Yes	N/A
#-Pin Motor Support	2 and 4 Pin Motors	2 Pin Motors	N/A
Number of methods provided	3	19+	N/A
Commented Code	Yes	Yes	N/A
Documentation	Yes	Yes	N/A

Table 16: Table Comparison Between External Stepper Motor Libraries

3.2.3.2 Libraries for Passive Stereoscopy

There are a variety of different computer vision software out there and each varies in their features and complexity. The following paragraphs will consider two free options for image processing software and will discuss their capabilities and suitability for the stereo vision system.

3.2.3.2a OpenCV

OpenCV is a very popular open-source library, developed by Intel, that is used for computer vision and image processing. OpenCV is versatile across many platforms because it supports multiple programming languages, including C/C++ and Python. OpenCV has many tools for filtering, edge detection, image processing, and image transformation. It includes algorithms for object detection, for feature detection and matching, and for stereo vision and depth estimation. This library is extremely flexible and versatile. Some key features include image processing, computer vision algorithms, machine learning, video processing, and 3D reconstruction. For this reason, it is the go-to choice for many vision-based applications. For our use case, OpenCV is an attractive choice as it has various, useful tools for stereo vision applications. This includes tools for camera calibration, image rectification, creating disparity maps, and for depth estimation. [75]

3.2.3.2b SimpleCV

SimpleCV is an open-source, Python-based framework that is based on OpenCV. It was created to provide a friendly framework for beginners to develop their own computer vision applications. SimpleCV is easier for beginners to digest as it does not dive deep into the complexities of algorithms. For this reason, SimpleCV is limited in its capabilities. SimpleCV features functionality for image capture and processing, object detection, and real-time processing. However, it does not include functionality for more advanced computer vision tasks, like 3D stereoscopic reconstructions. For these reasons, SimpleCV was not selected. [76]

3.2.3.2c TensorFlow

TensorFlow is an open-source, machine learning platform with a large set of tools, resources and libraries. It can be used for building and deploying computer vision applications that are supported by machine learning. TensorFlow is capable of facial recognition, image classification, and object detection. However, the platform has a steep learning as it utilizes machine learning algorithms to improve the quality of imaging tasks. Using TensorFlow for our application in a stereo vision system would add unnecessary complexity as we would need to train deep learning models to work. [77]

3.2.3.2d Table comparison of software for passive stereoscopy

	OpenCV	SimpleCV	TensorFlow
Price	Free and open-source	Free and open-source	Free and open-source
Primary Purpose	Computer vision and image processing	Simplified interface for computer vision tasks	Machine learning and deep learning
Ease of Use	Moderate, involves coding knowledge	High, easy to use and beginner friendly	Moderate to difficult, requires knowledge of machine learning
Programming Languages	C++, Python, Java, JavaScript	Python	Python, C++, JavaScript, Swift, Java
Image processing capabilities	Extensive	Basic	Limited (mostly for data preprocessing)
Stereo vision capabilities	Stereo vision and depth maps	Basic	Limited
Video processing	Real-time video and image processing	Basic video support	Limited, other libraries necessary for integration

Table 17: Table Comparison of Software for Passive Stereoscopy

3.2.3.2e Software Summary + Selection for Passive Stereoscopy

There are a variety of computer vision libraries out there but for our applications we have chosen OpenCV. This is because OpenCV is a versatile library with many functionalities that are useful for our applications. It is also compatible with a variety of platforms and in different programming languages.

3.2.4 ECAD Software for PCB Design

In order for the Solder Paste Dispenser to be realized, all of the electronics must be housed and connected within a custom designed printed circuit board (PCB). There are plenty of computer-aided design (CAD) software that can help with designing said PCBs. Each software program has the same core features, but with slight differences between them. When determining the CAD software of choice, there are some main considerations the team will keep in mind. The first few

considerations are regarding the interior of the software itself and its main features such as the components library, the software's compatibility, the GUI, and whether the team can collaborate on it via an online repository. The second set of considerations are regarding the exterior of the software such as the team's prior experience with the software, whether the software follows industry standards or is used widely by the industry, any extra available online resources to help navigate the software, and finally the price of getting a license to use the software.

Most ECAD software has the same core features and functionalities that are worth getting familiar with before jumping into design and knowing what is worth comparing between software. For example, every ECAD software includes a schematic design followed by a PCB design. This simply means that the software allows the user to initially design the circuit on a 2D plane, defining all of the components and connections prior to routing it all on the 3D viewer. Multiple schematics can be made and there are plenty of features allowing for more complex circuits to be realized by using ports, buses, etc. Components can be selected from the library the software provides or downloaded from third party component marketplace websites like Digi-key.

Once the 2D schematic of the circuit has been created, the user can make a new file for the PCB layout. The PCB layout is the 3D version of the circuit being designed. All of the software being discussed below will be able to automatically translate the designs from the schematic layout over to the PCB layout. That means that all of the connections and components will be translated from their 2D to their 3D counterparts. This layout lets the user virtually place the physical components where they want to. They can also choose the size dimensions of the PCB, the number of layers, etc. To prevent overlapping connections, complex designs use multiple layers to run multiple different connections for signals, power, ground, etc. Traces are the physical copper wires that run between components, thus connecting them. Vias are conductive holes that travel between layers also connecting components while preventing overlap.

On top of schematics and PCB layouts, most of these programs also have circuit simulations that the user can run in order to ensure their design is working properly. Design rule check (DRC) is a feature that checks for any clashes between the PCB's parameters, constraints, or requirements and the design itself. Any problems identified during DRC will be reported back to the user for them to fix. Once the user is done finalizing their design, they are able to create and share the Gerber files for their project. A Gerber file is a file format that describes the PCB and its layers. This standardized file can be generated within the ECAD software and then shared with manufacturers to build it.

Now that ECAD software features have been defined, there are many extra aspects to consider for PCB design: What systems and subsystems will the team require for its design? How will the board be laid out? How is everything being powered? How many layers, and as a result, how many vias are needed to realize the design? How will the housing for the PCB be made?

3.2.4.1 ECAD Software Considerations

To further elaborate on the first set of considerations, it is extremely helpful to have a live components library that is constantly being updated from component market websites such as DigiKey, Mouser Electronics, Ultra Librarian, Pololu Robotics & Electronics, and more. This allows the user of the CAD software to easily implement market products from the component library into their design without the need to manually import it from the website. However, in the event that a specific product is not included in the software's pre-existing live library, it is desirable for the software to be compatible with websites that do have downloadable CAD models. These websites often have an option to download and install a component's CAD model straight to the software of choice (given that it is supported by the product market website). Another feature that could prove to be useful would be the portability of the CAD software. It would also be desirable for the software to have the feature of being able to port or upload a schematic or PCB design from one CAD software to another. The selected CAD software should also be user-friendly with quick-to-learn GUI and lots of customizability/accessibility. This would also generally include all the exclusive features and functionalities that it can perform over other CAD software. Finally, it would be ideal for the software to have a collaborative feature for multiple team members to be able to view and modify the files virtually from an online repository. The team plans to use a GitHub repository to share and store most of their files and having access to the PCB there would be convenient.

The second set of considerations is meant to cover external factors surrounding the use of the software. For example, the prior experience of the team with the software is an important factor to hastily get accustomed to it and begin using it as soon as possible. With no prior experience, the team would require an abundance of online learning resources to help navigate the software. The availability of resources such as company-official tutorials, online forums/blogs that discuss problem-solving techniques, and company website Q&As would help alleviate the lack of prior experience. Another important factor is whether the software has features that help enforce manufacturer requirements and parameters to ensure the designed PCB can be manufactured. This is also related to whether the software is multifaceted and follows industry standards allowing for said manufacturability. With all those factors being considered, the final consideration is the price associated with the software. There are several options for pricing offers such as free downloads, free trials, standard paid licenses, enterprise paid licenses, student discounts, and free limited student licenses.

3.2.4.2 Industry Used ECAD Software

Now that the criteria for choosing PCB CAD design software have been defined, there are plenty to choose and compare from. Some of the most common industry standard PCB design CAD software programs are KiCAD, OrCAD, Cadence Allegro, Flux, Autodesk Eagle, and Altium Designer.

3.2.4.2.a KiCAD

Starting off with KiCAD, it is an open-source PCB CAD design software [78]. It includes a built-in library alongside some official library repositories (found on GitLab) for schematic symbols, PCB footprints, 3D models, source files, and project templates for multiple versions of the software. The system libraries can be kept up to date by manually cloning them using Git. It also supports third-party libraries from Digi-Key, Octopart, SparkFun, SnapEDA, and PCB Libraries. KiCAD also supports importing schematic and PCB designs from Altium Designer, CADSTAR, EAGLE, LTSpice, Solidworks, etc. KiCAD has a very simple user interface (UI) along with a schematic viewer/editor and a PCB viewer/editor. Layer views can be toggled on/off, there is a Gerber file viewer, and an integrated spice model simulator is available with customizable simulation settings. There are plugins, library, and color themes repositories that can be used from the KiCAD website. KiCAD files can be pushed to a Git repository allowing for team collaboration.

The team has had little to no experience using KiCAD. However, there are plenty of official learning resources and external tools that KiCAD provides on their website. They also have a “Community” tab on their website that links to chats, forums, and mailing lists [79]. Since KiCAD has a Gerber file viewer and export feature, it can be sent to manufacturers. Finally, KiCAD provides a General Public License (GNU) which means it is free software for download and distribution.

3.2.4.2.b OrCAD

Moving on to OrCAD, it is a PCB design tool from EMA Design Automation (a Cadence partner). OrCAD includes an integrated, up to date library and is also supported by Ultra Librarian and SnapEDA for component/part downloads. The standard version of OrCAD X supports Altium Designer, AutoDesk Eagle, and PADS translators to be able to import/export designs between these software. OrCAD has a plethora of extra features including allowing the user to save different versions of the same design. In addition, a design difference feature allows the user to see the differences between revisions, the “cross probing” feature lets the user see both the schematic and PCB view at once while communicating simultaneously, and a symphony collaborative feature that allows multiple users to

simultaneously work on the same project at the same time [80]. OrCAD also uses generative artificial intelligence (AI) for component placing, routing, etc. OrCAD also has PSpice implementation. While OrCAD files can be pushed to a GitHub repository, it does not have seamless integration for the aforementioned version control feature, meaning it would have to manually be pushed every time the user seeks to update the project.

The team has had no prior experience with OrCAD. However, there are plenty of online resources such as the Cadence community forums, EMA academy (courses and videos that teach new users), expert training, the How-To-Library, and many other forms of support. OrCAD can generate the necessary Gerber files to send to manufacturers and be imported from other CAD software. Lastly, for pricing there are many options to choose from. Each option has different licensing categories such as Time-based Floating License (TBL), Perpetual Floating License, and Time-based Single User License (SUL). Focusing solely on Time-based Floating License, OrCAD X Standard is unavailable (the standard package which brings OrCAD X and PSpice is \$1,280.00 per year), OrCAD X Professional is \$2,738.00 per year (OrCAD X Professional package brings PSpice Designer Plus, OrCAD Capture CIS, and OrCAD PCB Designer for \$5,520.00 per year), and OrCAD X Capture is \$650.00 per year. There are also certifications, training, and workshops available that vary from being free of charge to priced. Despite these steep prices, there is a professional free 30-day trial and for students there is a free 6-month trial with proof of enrollment [81].

3.2.4.2.c Allegro

The next CAD software is Cadence Allegro, one of the more common PCB CAD software used in the industry. Both OrCAD and Allegro are affiliated with Cadence and are very similar. Allegro has an up-to-date library and is compatible with most component websites just like OrCAD. It has integration of certain tools from Autodesk Fusion and Solidworks. Some of those similar features include version control, concurrent PCB design where multiple users can work on the same project at once, and generative AI techniques for PCB layout [82]. Overall, Allegro has almost every feature that OrCAD has in addition to some more complex, higher-level functionalities regarding vias, layers, routing, and traces. While OrCAD is often used in simpler projects for schematic designs, Allegro is used more often for PCB layout [83]. It can still be pushed onto GitHub repositories.

The team has had no prior experience with Allegro. Similar to OrCAD, there are countless videos and training courses that Allegro provides [84]. The price for the Allegro PCB Design package (which brings Allegro PCB Designer, Allegro System Capture, and PSpice) is \$1,500.00 per month. There is also a 30-day free trial for all package types of Cadence Allegro. In addition, a student free trial can be

requested which will put the user in contact with a Cadence team member to find out more information, but it is not directly downloadable.

3.2.4.2.d Flux

A much more recently launched PCB design CAD software is Flux. This browser-based software heavily utilizes artificial intelligence (AI) for its schematic and PCB design. It has a community components library which allows parts to be shared by owners and the user can share their own parts [85]. Components can be imported directly from KiCAD, Eagle, SnapEDA, and Ultra Librarian. As a result of the heavy AI usage, this CAD software has very unique features such as being able to extract and convert component information from its datasheet to be able to use it in the design. When designing the schematic or PCB layout, the user can ask the Flux “Copilot” AI a question to help answer questions, refer to datasheet information, perform actions on the schematic, and even navigate the UI. The schematic can be tested with the built-in simulator based on LTSpice. It can also generate and export Gerber files along with a bill of materials. Flux also provides version control and projects can be shared with others for collaboration [86]. Flux’s collaboration feature allows it to act as its own repository, however since it is browser-based it cannot be pushed into the team’s pre-established GitHub repository.

Some members of the team have little experience with Flux, but there are many resources available on the official website. The website’s search bar also has AI implemented in it meaning that any question regarding the software can be answered and the AI will provide the source for where it received the answer if the user sought more information. In addition, if the user has not fully learned how to navigate through the software, it can simply ask Copilot for help, removing the possibility of a steep learning curve. The official website also includes some informative videos and tutorials to help prepare new users for schematic and PCB design. There are multiple plans to choose from for individuals planning to use Flux. The “Basic” free plan allows users to have 5 private projects, unlimited public projects, full design capabilities, and the AI Copilot. The “Pro” plan for \$12 per month (or free for students and educators) provides unlimited private projects and unlimited editors on top of the basic plan features. The “Ultra” plan for \$24 per month provides all the aforementioned features along with extra support and a private community. There are also business plans like “Organization” for \$39 per month and “Enterprise” with custom pricing which include more logistical features.

3.2.4.2.e Eagle

The next CAD software that will be evaluated is Autodesk Eagle. This electronic design automation software is integrated with Fusion which is a general CAD software platform offered by Autodesk [87]. Eagle supports an up-to-date,

managed library, it allows users to download libraries, and users can also create their own personal libraries. Libraries can be manually refreshed within the software to automatically update any components or component information while working on a design. Eagle does support version control via online repositories like GitHub. Eagle has a Spice simulator, obstacle avoidance routing tools, generative AI capabilities, and 3D component models. The Eagle and Fusion integration allow for simultaneous ECAD (electronic computer-aided design) and MCAD (mechanical computer-aided design) within the software platform. This could speed up the process of designing the PCB through ECAD and the housing for it through MCAD.

The team has had the most experience using Autodesk Eagle considering it was the University of Central Florida's ECAD of choice for the Junior Design course. The Autodesk website provides plenty of additional online resources like blogs, forums, videos, courses, and certifications for Eagle. The software is also capable of generating and exporting Gerber files for manufacturers. Eagle licenses cannot be purchased by themselves since Autodesk is currently in the transition of fully implementing Eagle into Fusion as a single program. To buy an Autodesk Fusion subscription with Eagle included it would typically be \$680 per year for a single user. There also happens to be a Fusion 30-day free trial with all features, a Fusion for personal use (hobbyist) with limited features, and a Fusion for students that grants all features [88].

3.2.4.2.f Altium Designer

The final ECAD software that will be considered is Altium Designer. Similar to Cadence Allegro, Altium is quite common throughout the industry for PCB CAD designs. Altium has an up-to-date, components library with a manufacturer part search that allows users to choose backup parts for their design [89]. The library is connected to hundreds of suppliers such as Octopart and IHS Markit and components can also be downloaded from supplier websites and imported into Altium to create a personal library. Altium also has an "ActiveBOM" feature where the bill of materials is automatically updated and checks for any supply or specification issues throughout the design process. This allows parts to be replaced quickly if there is an issue with an already selected part. The BOM can also be customized with different views, groupings, or even include different suppliers. Altium has built-in Spice simulations with circuit analysis and customizable parameters. It supports integration with MCAD applications like Solidworks and Fusion. Auto routing, using Altium Designer's Situs feature, will help users design their PCB layout by letting the software automatically route an optimal path especially when using polygon pours. A similar feature called ActiveRoute performs routing for signal nets and could re-pour a polygon if needed for routing optimization. Altium also internally supports Git version control systems allowing the team to push source files to the repository.

The team has had some recent prior experience with Altium Designer and there are plenty of resources to help learn and navigate the software. Altium provides forums, documentation, certification/training courses, and even a practice project for new users to try out [91]. Altium is capable of generating and exporting Gerber files to send out to manufacturers. Altium has a couple of options for pricing, there is a Perpetual License for companies starting at \$11,970 and Term-Based License starting at \$4,235 per year. Out of the Term-Based Licenses, there is a Standard version with basic features starting at \$4,235 per year, a Professional version with more advanced features starting at \$5,495 per year, and an Enterprise version with varied pricing. There are also free trials available to professionals, students, and startups. The professional free trial can last up to 30 days; however, the student free trial will last one full year upon verification of student status.

3.2.4.2.g ECAD Software Comparison

Each of these ECAD applications allow the user to create schematics, run circuit simulations, create PCB layouts, place components, insert vias, and run traces/routes. All of them also have updated libraries (or can be updated) and are compatible with other CAD software to allow for importing files from one to another. In addition, they all have a feature that creates a bill of materials, they can export Gerber files, they support flat/horizontal and hierarchical designs, they have design rules checks and design for manufacturing checks (which locate any unwanted or imperative design violations), and have some type of circuit simulation (spice, thermal, etc.). Where each software seems to differ is in automation of certain features (routing or BOM), quality of life improvements, use of artificial intelligence, level of collaboration, and licenses/prices.

For the applications that may not have internally supported Git, CADLAB is a third-party site that supports Git version control for Autodesk Eagle, KiCAD, Altium, OrCAD, PADS, and more. It currently supports pushing schematic and board layout file formats with library file formats coming soon. CADLAB can connect to GitHub, GitLab, or Bitbucket even if it is already being used for version control and saving source files in an online repository. This service can also compare source file code/text between each version [91]. It could be a useful tool for sharing, viewing, and annotating schematic and PCB layouts as long as it is supported by the ECAD application. CADLAB is free for individuals and free for open-source projects.

The table below shows the major features and information that was previously discussed. For reference, when the feature on the right side has “(Y/N),” the “Y” means “Yes,” and the “N” means “No/None.” The “H,” “M,” and “L” are for “High,” “Medium,” and “Low.” High on the collaboration features means that the program

allows multiple users to work on the project files simultaneously; a Medium means that it only allows for version control and multiple users to view/annotate the files; a Low means it only allows users to view/annotate files. Regarding the AI feature, a High means that there is heavy usage of generative AI along with various other forms of AI support; Medium indicates there is no AI design help, but it has other automated or machine-learning features; a Low means that there are only basic auto-routing functions and active bill of materials.

3.2.4.2.h Table Comparison Between ECAD Software

	KiCAD	EMA OrCAD	Cadenc e Allegro	Flux	Autodes k Eagle	Altium Design er
Live Library (Y/N)	N	Y	Y	Y	Y	Y
Download/Imp ort Components (Y/N)	Y	Y	Y	Y	Y	Y
Integration with other CAD software (Y/N)	Y	Y	Y	Y	Y	Y
BOM (Y/N)	Y	Y	Y	Y	Y	Y
AI (H/M/L/F)	L	M	M	H	M	M
Automated Features (H/M/L)	L	M	M	H	H	H
Integrated Git Version Control Support (Y/N)	Y	N	N	N	Y	Y
Simultaneous Collaboration Features (H/M/L/F)	L	H	H	M	L	L
Prior Experience (H/M/L/F)	L	N	N	L	H	M
Available Learning Resources (H/M/L/F)	H	H	H	H	H	H
Industry-used (Y/N)	N	N	Y	N	Y	Y

Simulator (Type)	NGSpice	PSpice	PSpice	LTSpice	NGSpice	MixedSim (Spice based)
Price for Low End Version (\$)	\$0	\$1,280/yr	\$1,500/yr	\$0	\$680/yr	\$4,235/yr
Free Trial (Length)	Unlimited	30 days	30 days	Unlimited	30 days	30 days
Student Version	Unlimited	6 months	30 days	Unlimited	1 year	1 year

Table 18: Table Comparison Between ECAD Software

Now that each has been compared, there are two ECAD software that provide the most features and functionalities: Autodesk Eagle and Altium Designer. Despite the team having the most experience with Autodesk Eagle due to the Junior Design course, Altium Designer is similar to navigate. Altium is also used in the industry by significantly more companies than Autodesk Eagle, showcasing its versatility. Autodesk also plans to stop selling and supporting Eagle by 2026 as they prepare to integrate it with Fusion. Learning and mastering how to use Altium Designer is a skill that will be more useful for the team upon completing this Senior Design project. As a result, Altium Designer will be the ECAD software of choice to proceed with for schematic and PCB design.

The next best software based on the table above would be Flux. Although the team lacks good experience with Flux and has no Git version control support, it will be able to provide plenty of AI tips and tricks when designing the PCB. For example, if the designer has questions regarding circuit theory or general good practices for designing, they can reach out to Flux to answer their questions. The ideal pair would be for the user to use Altium Designer as its primary ECAD software and then use Flux as an extra AI resource.

3.2.5 Image Processing Flow

Image processing encompasses a range of computational techniques used to manipulate and analyze images, represented as 2D or 3D matrices, to enhance their usability and to extract meaningful data. Software like MATLAB and OpenCV are commonly used for image processing, offering built-in functionalities for tasks such as filtering, edge detection, transformations, and more. Image matrices can also be manipulated mathematically using software making it possible to implement computer vision tasks. Image processing has a wide array of applications across fields; in medical imaging, for example, image processing plays a critical role in isolating and analyzing features in MRI and CT scans, allowing clinicians to detect anomalies like brain tumors. Techniques such as

segmentation, edge detection, and thresholding help identify tumor boundaries and distinguish them from healthy tissue, supporting accurate diagnosis and treatment planning. Another application involves manufacturing and quality assurance, image processing can be used to identify defects with speed and accuracy. This has a great impacts on the speed of quality assurance practices. Image processing has a wide variety of applications in many fields. However, it is important to note that when processing is done to an image, information is destroyed. Image processing utilizes techniques to selectively remove the information that is not needed. This filters out everything but the useful data in an image.

Beyond enhancing images, image processing can correct distortions introduced by optical systems. By characterizing a system's specific flaws—such as geometric distortions like pincushion or barrel distortion—it becomes possible to apply transformations that compensate for these errors, resulting in images that more accurately represent the true dimensions of a scene. For instance, a camera with a pincushion effect, where edges appear pulled toward the center, can be calibrated by mapping image points to their corrected positions. Techniques such as geometric transformations and warping adjustments make this possible and are critical for applications that require precision, such as robotics, satellite imaging, and medical imaging. Image processing techniques can also be used to correct some optical aberrations that could potentially be produced by an optical system.

Now we will discuss a general structure that image processing follows which can vary in length depending on the application. The first step involves image acquisition where the camera records the image. The second step is preprocessing. Images are preprocessed to prepare images for further processing and analysis. Preprocessing first involves compensating for camera distortions and lens aberrations based on known camera characteristics. Then basic adjustments can be made to remove unwanted artifacts, reduce noise, or adjust brightness and contrast in the image. For example, if there is noise present in an image, it is possible to filter out that noise using a low-pass filter like a boxcar filter, or you can use techniques such as Gaussian blurring. These filters can be optimized to reduce as much noise as possible while maintaining sharp, defined edges in the image. These filters work by removing undesirable spatial frequencies in the image. Preprocessing can also include resizing or cropping the image to isolate areas of interest. It is also possible to convert the color spaces in the image, for example, from RGB to grayscale.

Preprocessing also involves image enhancement. These image processing techniques are applied to enhance certain features or aspects of the image and

can also be used to improve the overall quality of the image. Filtering involved in preprocessing for noise reduction can inadvertently reduce the overall quality of the image with blurring. Image enhancements help adjust for this and usually consists of amplifying edges, contrast, or specific colors.

Finally, the image is preprocessed and ready for analysis, we can extract information from the image. Images can be split apart into meaningful regions using segmentation. Segmentation techniques include thresholding, edge detection, and region-based segmentation. These techniques commonly use algorithms like Canny edge detection, Sobel edge detection or watershed edge detection. If you want to detect features in an image, these features can be extracted using feature extraction methods such as Scale-Invariant Feature Transform (SIFT) or Speeded Up Robust Features (SURF). Then additional methods are used to match key points in an image. Additionally, machine learning algorithms are commonly used in conjunction with image processing techniques to enhance the performance of object detection and recognition.

Chapter 4 – Standards and Design Constraints

4.1 Related Standards

4.1.1 The Gerber File Format

Gerber files will be the format in which the consumers can provide information related to their PCB design. These standard file formats describe the physical layers that compromise the PCB. A typical PCB is composed of copper layers, solder masks, silkscreen, and a solder paste layer. Typically, each layer of the PCB design is represented as its file. This makes it easier for SDP as the information we need to locate the solder pads would be contained directly in the solder paste layer file. There are some important commands used within Gerber files that will be required to be parsed to efficiently extract the data, these will be listed below.

%FS is the format specification [92]; this decides how coordinate positions will be stored. For example, in Eagle, the default format specified is “%FSLAX34Y34*%”. This means that the X and Y coordinates contain 3 integers and 6 decimals. This is important as the SDP needs to be able to extract precious locations from the Gerber files.

%MO is for the Mode of Units. It specifies the units used within the Gerber file. The two main options are either “%MOMM*%” or “%MOIN*%” [92]. These stand for millimeters and inches respectively.

%TF stores the file Attributes. This can be anything from the software used, the name of the project, the date it was created, and more.

G-Codes refer to a set of commands that start with the letter G rather than a numerical number. They typically specify certain operational modes, drawing paths, and positioning. For example, “G01” represents linear mode [92]. The G01 mode followed by a coordinate with the “D01” command will draw a line from the current position to the position specified. The “G04” command is for comments, this can include any information that the file producer deems as important. For SPD, the “G04” command will typically be ignored. “G70” and “G71” specify the unit modes, they achieve the same goal as the mode of unit commands specified above.

D-Codes refer to the drawing commands. These are the specific commands that paired with the G-Codes enable the machines to draw the required tracks or traces. D-codes from D10 and onward specify data mapping to a specific aperture. For our project, these will specify the size of the Apertures used. The body of the paste Gerber files will contain callouts to specific apertures followed by a “D03” flash command [92]. These flash commands will specify an aperture to be “flushed” at a specific location. For our project, most of the pads will be specified like the following “X863600Y671322D03*” This is a flash at the X and Y coordinates specified.

4.1.2 ISO 45001

The ISO 45001 standard covers occupational health and safety requirements. These standards provide a strategic management framework that is designed to integrate safety into the workplace. The standards provide guidelines for companies to ensure that the workplace is safe. It provides guidelines for hazard identification and risk assessment. It also focuses on facilitating safety improvements, not just reducing the risk of injury. Considering the likelihood of utilizing laboratories to develop our systems, ISO 45001 applies to the development of this system. To ensure compliance with ISO 45001 when working in a lab, first, any potential risks or hazards must be assessed and identified. An example could be a high-power laser that may have high-voltage electrodes exposed. Following the assessment of risks and hazards, it is important to establish safety standards and procedures that address these safety risks. Safety standards and procedures include but are not limited to, the use of PPE and safety equipment, regular equipment maintenance, safety policy documentation, and incident reporting. Although our project itself may not pose any significant risks or safety hazards, it is still important to adhere to safety standards when working in a lab with other projects going on.

Most of the laboratory use will consist of optical and electrical system testing. Laboratory use is justified since optical and electrical systems are expensive, so it is important to be able to test various designs before ordering components. These labs provide the necessary equipment to quickly prototype optical systems. Considering that there are many senior design projects, it is likely that more than one team will be working on their project at the same time. There is a required mutual respect for each other's safety when working in a lab. There should be full transparency between groups as to what is going on in the lab so appropriate measures can be taken to ensure the well-being of everyone.

4.1.3 ISO 10110

The ISO 10110 standards are the standards used for specifying optical elements. It encompasses design drawings and table specifications. ISO 10110 drawings are typically divided into four main parts – the drawing of the optical component itself, and three columns below it that describe the left and right surfaces, as well as the material. By standardizing the layout of optical drawings for designers, manufacturers, and users; they can easily find the information they need from a specific optical drawing, and this makes it much easier for different disciplines that support the product to understand what is going on. The right column and left column describe the shape and specifications of the surface of the optic. The center column describes the material the optic is made of and its specifications. The specifications for the left, center, and right columns are standardized as well. There are 13 specification types, and they can either be specified or left empty on the drawing if irrelevant or not important. These specification types include general remarks, material stress birefringence, material bubbles and inclusions, material inhomogeneity and striae, surface form tolerance, centering tolerance, surface imperfection tolerance, surface texture, surface treatment and coating, data of lens element, non-toleranced data, aspheric surface detail, and laser induced damage threshold.

These diagrams are useful for extracting critical information needed for calculations and simulations. Fortunately, the Thorlabs website features export files for Ansys ZEMAX OpticStudio which makes setting up the optical simulation's much faster. We no longer need access the ISO 10110 drawing for the optical component. Although we are not using it, it is important to emphasize the use of standards for describing optical components to ensure efficiency and understanding throughout the chain, from production to user. These drawings are also useful for extra information that is not included in the ZEMAX file. It is always important to check requirements against ISO drawings.

4.1.4 EMVA 1288

The EMVA 1288 standard is a standard created by the European Machine Vision Association. It is a widely recognized guideline that standardizes the measurement and reporting of camera and image sensor performance for machine vision systems. This standard is used by camera manufacturers and exists to ensure that cameras and sensors are tested with consistency and comparability. This allows consumers to compare different sensors and cameras reliably. Measurements of key parameters like quantum efficiency, signal-to-noise ratio, dynamic range, and saturation capacity are all standardized. Although we are not directly designing and creating components like sensors, this standard is used in many of the components we have considered for the stereo vision system. Stereo vision component specifications and selections that are included in our project follow this standard.

4.1.5 IEC 62368-1

The IEC 62368-1 standard was introduced by the International Electro technical Commission (IEC) and enforced on December 20th, 2020. It is a safety standard dedicated to identifying energy sources and proposing safeguards against them. It should reduce injuries and damage for a wide range of technology products such as computers, networks, consumer electronics, displays, audio/video equipment, communications products, office appliances, and power supplies. It was initially introduced to supersede prior safety standards such as the IEC 60950-1 (ICT) and the IEC 60065 (AV). It is a standard flowed in the U.S., Canada, and the EU. Some of the safety concerns that the latest 4th edition brings up are electrically caused injuries and fires, along with thermal burn injuries by making changes to touch temperature limits allowed on certain products. Regarding switched-mode power supplies, it specifies that prior to supplying power it is required to use proper loads with specific characteristics for output voltage, current, or power to be measured. This standard can be found in many of the referenced switched-mode power supply datasheets.

4.1.6 IEC 60601-1-2:2014

The IEC 60601-1-2:2014 standard was introduced by IEC as a safety standard to reduce the emission of electromagnetic disturbances in devices that might be commonly used for Medical Equipment (ME). It specifies the necessary EMC Immunity test level that a device must abide by depending on its environment of intended use. It also provides clarification on how to test for and determine a device's immunity level depending on its intended use. The standard also elaborates on the criteria for what is considered a pass or a failure for EMC immunity. The fourth edition of this standard comes as a revision to replace the previous third edition. This standard was made for enforcement in the U.S. and the EU. However, it does not only apply to medical equipment as some of the referenced power supplies abide by these standards.

4.2 Economic Constraints

There is a huge economic constraint when it comes to making this project. Personalized solder paste dispensers typically range in the several hundred to several thousands of dollars to purchase one. For example, those sold by IntelliSpense can cost anywhere from \$7,700 to \$12,100. For high-end solder paste dispensing, this price can be justified as this is a very niche market and target audience that this product would be sold to. The alternative that the team is providing is still expensive, but significantly cheaper than those sold in the automatic solder paste dispenser industry.

The main economic constraint is simply funding for this type of project. Despite it being cheaper than commercial off the shelf products, it still requires a few hundred dollars to achieve, on top of the time it takes to put it together. For starters, the Ender-3 V2 Neo that the team is basing the design off of must be purchased in order for us to use its mechanical structure. The Ender-3 V2 Neo currently costs \$299.00 which is a requirement for this project to be realized. The downside to purchasing this 3D printer is that most of the money spent on it will be for a complete package that the user will plan to dismantle and not utilize. Many of the parts that the printer comes with will be rendered useless in order to adapt it into the solder paste dispenser. These parts include the display, PCB, power supply, motor drivers, stepper motors, heating bed, heating elements, and nozzle for dispensing.

Now that the user has purchased the Ender-3 V2 Neo and understands what components will not be used, they will then need to spend an estimated ~\$280 extra as mentioned later in Chapter 10.1 Budget and Financing. The team's design includes implementing a new MCU capable of delivering all the features needed, a new touchscreen display with a fresh UI, different stepper motors that grants higher precision, different motor drivers, a new power supply with regulators, and the cameras and optics system.

Now that the whole picture has been painted, it is clear to see that this project will cost upwards of around \$500-\$600. Luckily, the project has been sponsored by Dr. Arthur Weeks which grants the team the ability to design a more complex and intricate solder paste dispenser. It is a relatively expensive system to make and variables such as price or component availability might complicate the process further. For the current design and path of development, the solder paste dispenser made by the team will be as efficient, cost-effective, precise, and reliable as possible.

4.3 Time Constraints

In order to create and/or replicate the design of this solder paste dispenser, it would take not only a lot of money but a lot of time and effort. One would need to purchase the pre-existing structure of the Ender-3 V2 Neo and then implement the rest of the design by the team on their own. The time constraints are mainly within the building out all of the aspects of the solder paste dispenser rather than any other types of constraints.

The team must meet their milestones and soft deadlines earlier than the actual due dates. Missing milestones would result in a snowball effect that leads the team to progressively fall even farther behind schedule. When it comes to senior design as a course in each team member's degrees, it is of utmost importance that each member puts all of their effort into this project to ensure it works. If the project were to be unsuccessful, it would result in repeating an extra two semesters prior to being able to graduate. This is a huge time constraint as senior design only offers two semesters for students to plan, prepare, design, and implement their projects. Senior Design I is meant to cover the planning and preparation phase when all of the report deadlines are due. Senior Design II covers more of the design and implementation phase when the actual construction of the physical device occurs. By the end of Senior Design II, it is expected to have a fully functional and reliable automatic Solder Paste Dispenser.

The team is fortunate enough to work under the guidance of Dr. Arthur Weeks, who has a general idea of the end result of this project. This helped the scheduling of our milestones since Dr. Weeks laid the groundwork for what results are expected of the team. The goals and objectives that were set in the original Divide and Conquer document were inspired by Dr. Weeks original concept of the solder paste dispenser.

Considering the grand importance of this project, it is in the best interest of each team member to ramp up production and put as much time and effort into this. Not only will this project be a success through our efforts, but it will be and has been a great learning and research experience.

4.4 Equipment Constraints

This section details the equipment constraints impacting the design and development of the solder paste dispenser project. Given the nature of the project, certain equipment limitations may affect the precision, scalability, and functionality of our design. For instance, the 3D printer available for prototyping optical components and housing has specific resolution limits, which may impact the fine

details necessary for achieving optimal alignment in the optical system. This will require testing and iterating to improve optical alignment.

The computational hardware available, such as mini-computers or microcontrollers, must support real-time image processing. This constraint may limit our choice of image processing algorithms, as more computationally intensive methods may be infeasible without higher-end hardware, such as a GPU-equipped computer. Although this constrains our design, there are workarounds that can be made, such as off-loading processing to another computer or other computational hardware.

Finally, access to specialized lab equipment, such as high-quality optics and calibration tools, may be restricted due to budget or availability, impacting the achievable accuracy of our stereo vision system. Recognizing these constraints, we will adapt our design to work within the limitations of available equipment while exploring alternative methods or tools as feasible to meet project requirements and potentially purchasing equipment if needed.

4.5 Safety Constraints

This section addresses the safety constraints associated with designing and developing the solder paste dispenser project. This section will focus on the handling of hazardous materials, safe equipment operation, protective measures, and the overall safety of the final product. First, working with solder paste presents potential health risks due to exposure to fumes and chemicals, which necessitates proper ventilation where applicable.

Electrical safety is another critical consideration, as our system involves the integration of various electronic components that require careful handling to prevent shocks, short circuits, or overheating. Proper insulation and grounding are essential to reduce electrical hazards during both development and operational phases.

Safe handling practices are required for any tools and equipment used in assembly and testing, including the 3D printer and soldering tools. Proper training and adherence to safety protocols are mandatory to prevent burns, cuts, or other physical injuries. By addressing these safety constraints, we aim to create an environment that prioritizes user well-being and aligns with lab safety standards. This also includes the use of personal protective equipment (PPE) where necessary.

The solder paste dispenser is comparable to a 3D printer regarding safety. Maybe even safer as we do not require any heating elements to dispense the solder paste. For safe operation, users should avoid placing their hands in the motors or in the region of dispensing during operation. When modifying or repairing the dispenser, the dispenser should be off and unplugged. To ensure safety, transparent documentation regarding operation and repair will be provided to users.

4.6 Environmental Constraints

This section outlines the environmental constraints associated with the design and development of the solder paste dispenser project and focuses on sustainable material usage, waste reduction, and energy efficiency. The project involves the use of materials such as 3D printing filaments, electronic components, and solder paste, all of which present potential environmental impacts. Where possible, we aim to select eco-friendly materials and minimize non-biodegradable waste. Additionally, we are committed to responsible waste management practices, including the proper disposal of electronic components and hazardous materials, such as printing filament or solder paste, to reduce environmental harm.

Energy consumption is another factor under consideration. We aim to optimize the power usage of our system to reduce its environmental footprint. By designing for energy efficiency, we hope to limit the system's impact on resource consumption.

Lastly, emissions and byproducts generated from processes like 3D printing and soldering are managed through adequate ventilation and by selecting low-emission materials where feasible. These measures reflect our commitment to minimizing the environmental impact of the project, contributing to a more sustainable development approach.

4.7 Manufacturability Constraints

When it comes to the manufacturability of the Solder Paste Dispenser, there are a lot of factors to consider. As previously mentioned, the 3D printer that this solder paste dispenser is being built upon is only being used for its mechanical structure. The other components of the printer are simply inspiration for what the team seeks to achieve. The mechanical structure of the printer does not need to be manually manufactured, just simply purchased. This includes other design requirements like the power supply, stepper motors, etc. The optical system that is currently still being researched and developed will require a certain level of assembling to achieve. The lenses and cameras themselves will not be manufactured by the team, they will simply be purchased and put together.

On the other hand, the PCB is the main component that requires actual manufacturing to be outsourced. The PCB houses a plethora of components from microcontrollers to active components like op-amps to basic passive components like resistors, capacitors, and inductors. As a result, one of the biggest constraints regarding manufacturability is the availability of the necessary components. There are plenty of replacements for components in the event that any of them are unavailable to have long lead times, however the user would need to communicate with the PCB manufacturer to resolve this issue. The cost of making the PCB could range anywhere from a few tens of dollars to about one hundred dollars.

All of the ECAD software that has been discussed in prior chapters are capable of creating the necessary Gerber files to submit to manufacturers for them to begin building it. However, each manufacturer has different design constraints that must be discussed prior to designing the PCB for this project. For example, traces and vias might have a strict minimum size that the manufacturer requires the designer to abide by in order to ensure it is manufactured correctly. This is due to the fact that different manufacturers have different industrial machines with different precision and tolerances. Of course, as the design of the PCB becomes more complicated/smaller, that results in stricter economic constraints to fully realize the design.

The PCB design should also be simple to install and connect with the other components of the solder paste dispenser. It must be taken into account that different users with varying levels of experience might seek to replicate or handle this device. Thus, the manufacturing constraints are a very important aspect of the solder paste dispenser.

4.8 Ethical Constraints

This section will discuss the various ethical constraints associated with the design, development, and use of the solder paste dispenser project. This section is important to understand and ensure legality and responsible use of technology. We will discuss intellectual property concerns that are necessary to ensure that the solder paste dispenser project respects intellectual property.

In terms of intellectual property, we commit to adhering to licensing requirements and giving proper credit where necessary. Hardware and software components may vary in licensing terms; open-source components typically require attribution, while proprietary ones generally mandate licensing agreements. Although we do not intend to commercialize this product, we will provide appropriate credit and meet all licensing obligations, reflecting our respect for the intellectual property of others.

Another consideration for ethical constraints is the safety of the device. Ensuring user safety is a top priority in our design choices. We are taking steps to minimize potential hazards associated with solder paste and other components, such as reducing exposure to fumes and ensuring electrical safety. Additionally, we are mindful of the environmental impact of our materials, including the waste generated from 3D printing and electronic components, and aim to use sustainable materials and safe disposal methods wherever feasible.

If data collection or connectivity is involved in any part of this system, we are committed to protecting user privacy and data security, ensuring that all data is stored and handled responsibly. Furthermore, we will uphold transparency and accountability in our design process by openly sharing project limitations, potential risks, and ethical commitments to encourage responsible and beneficial use of this technology.

4.9 Sustainability Constraints

This section examines the sustainability constraints affecting the design and development of the solder paste dispenser project, with a focus on material durability, resource efficiency, and environmental impact over the product's lifecycle.

One key consideration is the choice of materials for 3D printing. While 3D-printed parts offer flexibility, the filament materials commonly used, such as PLA or ABS, may not be biodegradable or highly durable. We aim to select materials that balance durability with reduced environmental impact.

The project's end-of-life disposal also poses a sustainability constraint. Electronic waste from components like circuit boards and sensors contains hazardous materials that need responsible disposal. We are committed to following appropriate e-waste recycling practices for all electronic components and appropriate materials. Furthermore, our approach to design includes consideration of long-term usage. We aim to create a system that is durable and maintains performance overtime, reducing the need for frequent replacements, and thus reducing waste.

Energy consumption is another sustainability factor. The project involves components that require electrical power, including the stereo imaging system,

processors, and motors. To mitigate energy use, we will explore energy-efficient designs and power management techniques wherever feasible.

Chapter 5 – Comparison of ChatGPT

5.1 Introduction

ChatGPT is a very useful artificial intelligence (AI) tool developed by OpenAI that is designed to interact with users in a “conversational way” [93]. It is a generative language model that is trained to perform tasks such as answering questions, generating text, processing audio, and much more. The approach used to train this model is called reinforcement learning from human feedback (RLHF). This was achieved by feeding prompts to ChatGPT and having groups of humans pick their preferred response provided by the AI model [94]. This process helped clean up the model to try to avoid responding with mistakes, false claims, and other erroneous material. However, this AI model is still being worked on as it is currently in version GPT-4 and it still has plenty of limitations.

According to OpenAI, ChatGPT may respond with incorrect answers since there is no objective “source of truth” that the model was trained to grab information from. In addition, if OpenAI was to make the model more conservative with its responses, it might lead to not responding to a question all together. The model currently might provide different responses based on the way the prompt is worded by the user. With that in mind, ChatGPT might take some freedoms and assume what the user is asking without clarifying it with further questions. On top of all of those limitations, OpenAI is trying to optimize the model as much as possible to prevent it from utilizing biased data, behaviors, and responses in order to provide the most comprehensive replies [95].

5.2 ChatGPT for Power Supplies

With that being said, there are some ways in which ChatGPT can prove to be useful for engineering projects such as this Solder Paste Dispenser. For example, the team asked ChatGPT to provide various other commercial off-the-shelf power supplies that are similar in specifications to the one that is used in the Ender-3 V2 Neo along with some resources to find more information on them. The response it provided was very well-informed as it listed off five different power supplies, some “key features” that the user should consider when choosing a power supply that fits their needs, and some links to popular electronic components marketplace websites. It first described the type of input the Ender-3 V2 Neo uses along with the type of power supply (switch-mode power supply) that it is. It also follows a format for the list starting with the input voltage, output voltage, power rating, frequency, features, and where it is available for purchase.

However, a few issues arose when it began to list off different power supplies. Out of the five power supplies it provided, only three of them were useful and/or unique. The list consists of the Mean Well LRS-350-24, RS PRO 24V DC 350W, S-350-24 Power Supply, Mean Well RSP-320-24, and the BTF-Lighting LRS-350-24. The first three aforementioned power supplies were good recommendations from ChatGPT upon further researching the parts, but the final two were not. The Mean Well RSP-320-24, while being a real power supply, does not match the power rating (350W) of the Ender-3 V2 Neo that even ChatGPT acknowledges in the conversation's following paragraph. It closely matches the specifications, but the output current rating and output power rating do not match the requirements for the 3D printer. Then, the fifth and final recommendation of the BTF-Lighting LRS-350-24 is simultaneously erroneous and a duplicate of the first power supply made by Mean Well which was suggested. BTF-Lighting is mainly a lighting and LED company that sells multiple LED products ranging from matrix displays, modules, pixel strips, chips, and controllers [96]. They do happen to sell power supplies, but they are not manufactured nor designed by BTF-Lighting (rather they are made by JSPower). There is one power supply that is sold on the BTF-Lighting website that is capable of surpassing the power rating, but again it is not made by them. In addition, the power supply is also not called the LRS-350-24.

After listing off the power supplies, ChatGPT provides a section discussing the main features to focus on when looking for a power supply. It includes the required input voltage range, output voltage, power rating, protection features, form factor, and method of cooling. After this, it provides a few links to marketplace websites for electronic components to help steer the user in the right direction looking for more parts [97].

Overall, ChatGPT was able to help steer the team in the right direction and provide a reference of what the type of power supply is and where to find them. For example, ChatGPT helped locate Mean Well, which makes multiple different 350W switch-mode power supplies that meet the requirements for the Ender-3 V2 Neo. The features section also gave the team an idea of what to look for in these power supplies. There are multiple factors when choosing one, but ChatGPT provides a good start for users who might be new to the power supply industry.

5.3 ChatGPT for Optical System Design and Software

For assistance with optical design, large language models (LLMs) like ChatGPT are helpful for researching and finding information; however, doing things like calculations or making connections between optical concepts is a challenge for these language models. If they have not been trained on the information they are being asked, LLMs will hallucinate.

ChatGPT was particularly helpful in providing formulas and information to make the connections between different requirements, specifications, and parameters obvious. Making connections between numerical aperture and depth of field was easy with ChatGPT, all you had to do was have a conversation with it and ask questions where necessary. However, verifying what the model gives you is important as it does not usually provide any sources for the information it spits out. The LLM was also useful for retrieving and tabulating information about potential component selections for the optical system, although the information in the table had to be verified because some of the information given about specific products was not accurate.

When asked which existing optical designs may relate to our project, the language model failed to go into depth about any specific optical design that could be used as inspiration for our project's optical design. Overall, for the optical design, ChatGPT is not very useful. It is great for sourcing and finding components on the market but for figuring out what could be used to successfully realize our requirements, it failed.

Regarding researching the image processing and the design of the software for stereo vision, ChatGPT was extremely helpful. ChatGPT, in general, is helpful when it comes to programming tasks. This is because most information regarding programming and troubleshooting can be found on the internet, which ChatGPT is trained on.

When provided with the requirements of the software for stereoscopy and what needs to be achieved, the language model spits out a general software pipeline for processing the images for stereoscopy. This guideline was used to explore different aspects of the pipeline, like preprocessing techniques, image rectification techniques, etc. The language model was useful for finding information regarding image processing and helped improve understanding of specific concepts related to the software. One case is when we had to compare and decide on which pixel-matching algorithm to use. There are a variety of different pixel/feature matching algorithms in OpenCV, and ChatGPT was useful for understanding how they function and was useful for finding which algorithm fit our requirements the best. It was fantastic to compare these algorithms regarding computational intensity and potential point density. Then using these comparisons, we can select exactly how we want to process our images, calculate disparity, and generate a 3D point map. Overall, when it comes to assisting with programming and troubleshooting, ChatGPT is extremely useful.

5.4 ChatGPT for Code Generation

ChatGPT also is starting to be used by many to start making programs by generating code to get towards a baseline which mostly likely still needs to be modified to get towards a working version of what the user wants the code to do. ChatGPT usually can generate some boilerplate code which can be a great jumping-off point to creating and finishing the program. It is also great to get ideas on how the code should begin to look like, especially if the code being generated is in a programming language or using a library that the user is not generally knowledgeable about yet. Our team wanted to see if ChatGPT could generate some code to get a head start on making the code for the user interface of the display.

From the ChatGPT discussion and the prompt used, ChatGPT had some good ideas on how to begin making the program [98]. At the start of the program, it included the library specified, `TFT_eSPI`, and used the library throughout the program. Next, it defined some integers to help when drawing buttons on the display. It then made an enum to control menu states. Also, it defined some parameters for x, y, and z motor coordinates and made some function declarations. Currently, it has an overall good start in defining some reusable values, adding the library, and declaring the functions it will be using in the program.

ChatGPT then made the two crucial functions for the program which are setup and loop. They are the main two functions used in the `TFT_eSPI` library to control what is initially done at the start of the program in setup and what is done periodically for the rest of the program in loop. In the setup function, it initialized the tft object to control the screen, set the rotation of the screen, set the background color of the screen, and called the function to draw the main menu. In the loop function, it made some great code to grab coordinates of any touches on the screen and checks which button was pushed by the coordinates returned from the touch. In the loop function, it added a switch case based on menus to change button touch functionality based on which menu is being used, and it left the extra screen menu switch cases blank for further functionality later which is novel.

ChatGPT also made some functions for the different screens and a helper function. For different menus, it made the functions: `drawMainMenu`, `drawPrintMenu`, `drawFileSelectionMenu`, `drawManualModeMenu`, and `drawImageSelectionMenu`. The helper function it made was `isButtonPressed`.

The `drawMainMenu` function was made to make the main menu on the display. It first started with setting the background color and text color. It then has an interesting approach of making buttons by drawing rectangles and then printing

text within the rectangles. It does this to make the following buttons for file selection, manual mode, and image selection.

The drawFileSelectionMenu function was made to make the menu to select files to print from. It first started with setting the background color, text color, and adding the text "File Selection: " at the top of the menu. It also adds text as place holders for files with extension Gcode which is what a 3D printer would use, but they will have to be Gerber files for our purposes. It also does not attempt to make the files selectable which will be needed.

The drawManualModeMenu function was made to make the menu to manually control the stepper motors of the printer. It first started with setting the background color, text color, and adding the text "Manual Mode: " at the top of the menu. It does add printed text and displays the positions of each motor. It also made buttons by drawing a rectangle and putting text within it to adjust the x, y, and z coordinates. Unfortunately, the buttons don't indicate how the x, y, and z coordinates are adjusted. We would have liked to see ChatGPT have two separate buttons for each coordinate, plus and minus, to change the coordinate values.

The drawImageSelectionMenu function was made to display images captured by the printer. It first started with setting the background color, text color, and adding the text "Image Selection: " at the top of the menu. It then just added placeholders of just printing the images on the display.

The drawPrintMenu function was made to draw on the display of the main menu. It set the background color, the text color, and printed the text on the screen "Print Menu: " which is a good start. It then prints what the selected file is on the display. We would have liked ChatGPT to show many files to select from on the menu. It also draws a rectangle and text for a button to start a print.

The final function it made was isButtonPressed to return true if a button was pressed. This is used in conjunction with all the makeshift buttons ChatGPT made with rectangles and text through all the menus.

ChatGPT made an effort to make all these menus, but it seemed each to fall somewhat short. It is a bit disappointing though that ChatGPT did not opt to use the part of the library that implements buttons in one line which makes a rounded rectangle with text inside. This would have made the code easier to understand and implement. Also, the isButtonPressed could have been removed as the library can handle if any of the buttons were pushed. It did a great job though on making

some template of functions in which one could start to modify and clean up to get to a working version of what the program should look like.

5.4 Conclusion

Nonetheless, ChatGPT can provide good suggestions for a variety of possible subjects meanwhile spewing out nonsensical results or data about half the time. It is up to the user to research further based on the general ideas given by the response of the AI model. In addition, users who seek more detailed responses must ask more questions or even challenge the model by giving it even more prompts to induce better and desired outputs.

Chapter 6 – Hardware Design

6.1 Hardware Overview

The hardware for the Solder Paste Dispenser hosts the software and mechanisms to perform the actual solder paste dispensing. The primary hardware components include the custom PCB, stepper motors with motor drivers, optical system, and the frame of the Ender-3 V2 Neo. Each subsystem's design will be elaborated upon below using simplified block diagrams. In addition, if the team has already begun drawing up schematics or a PCB design, then screenshots from Altium Designer will also be included below. The schematics are a work in progress and will be updated upon any major changes.

6.2 MCU Subsystem

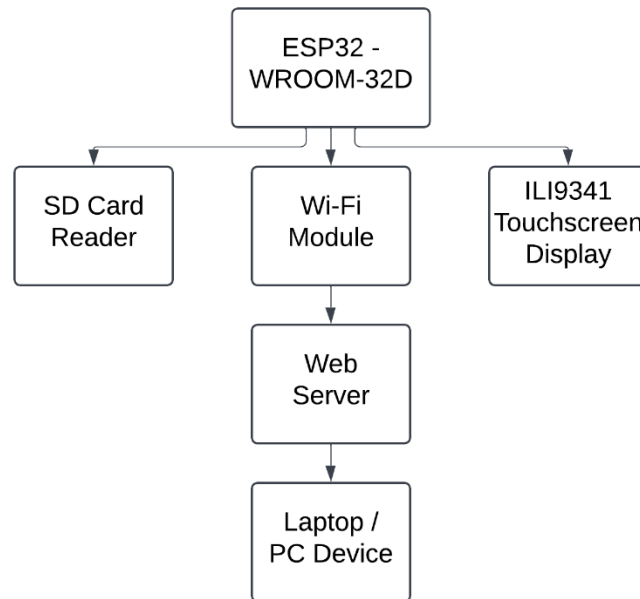


Figure 16: MCU Subsystem

As seen in the hardware block diagram above, the main MCU will consist of three major components: the microcontroller processor, an SD card reader, and a Wi-Fi module. The touchscreen display will also be attached to the main PCB, but of course it will be exposed for the user to interact with it (no housing over the display). The microcontroller of choice is the ESP32-WROOM-32D, the touchscreen display of choice is the ILI9341. The SD card reader will be put together using a basic SD card port and some resistors and capacitors to limit the current.

This will connect and communicate with the touchscreen display via SPI. As shown in the Altium Designer screenshot below, the ILI9341 display is powered through the VCC pin by the same 3.3V that the ESP32 uses. The display's LED is also powered by the same 3.3V. The ILI9341 connects to the ESP32 via GPIO SPI pins. The ESP32 must interface with the ILI9341 via SPI pins in order to properly communicate. The MOSI pin allows the ESP32 to transmit data to the display; the MISO pin allows the ESP32 to receive data from the display; the SCK pin provides the clock signal that ensures synchronization during the data transfer between the ESP32 and the display; the CS pin selects the slave device that the master (ESP32) wants to begin communicating with.

The ILI9341 display contains a built-in SD card reader that will not be utilized in our design. However, an external SD card reader will be implemented instead to interface directly with the ESP32. That is why the schematic below shows pins A1 (SD_CS), A2 (SD_MOSI), A3 (SD_MISO), and A4 (SD_SCK) not connected to anything on the ESP32. If the built-in card reader was to be used, they would connect via SPI pins to the ESP32. Finally, pins MH1 to MH4 are the mounting holes that will be used for the actual 3D PCB design. Depending on the PCB design, the team might choose to connect these mounting holes to ground. The following schematic will provide more information on SD card usage and schematics for it.

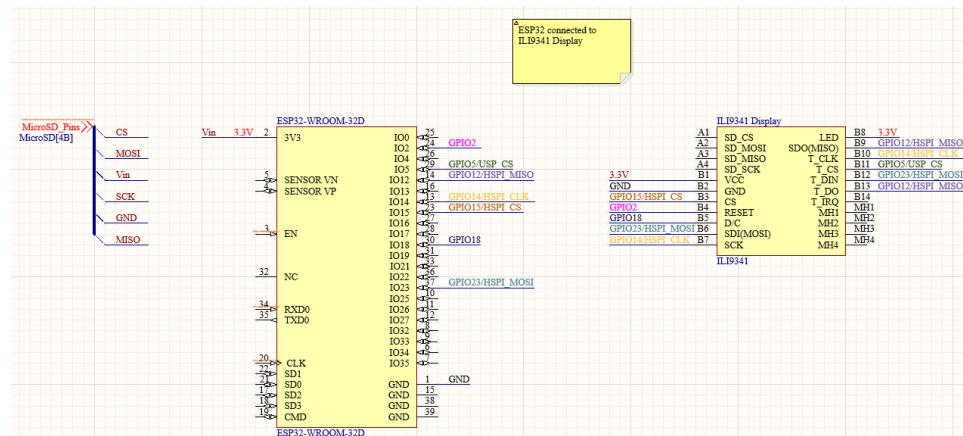


Figure 17: ESP32 to Touchscreen Connections

Despite the aforementioned Wi-Fi module seeming like a separate component in the hardware block diagram, the team opted for a model of the ESP32 that contains a built-in Wi-Fi antenna. The ESP32 will connect via its Wi-Fi antenna to a web server that is hosted on a laptop/PC device. The user will upload their Gerber files to the web server, which will communicate with the ESP32 to temporarily store that Gerber file data on the external SD card. The screenshot below showcases the SD card reader schematic.

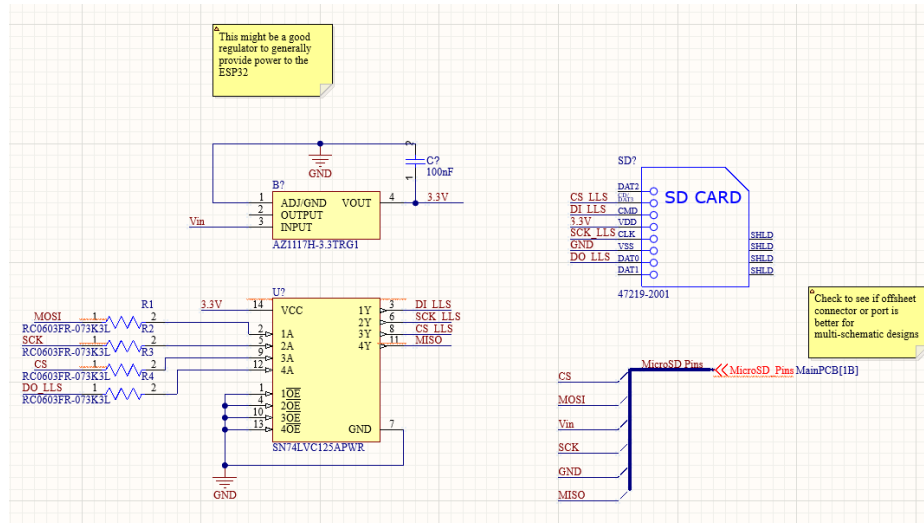


Figure 18: SD Card Reader Schematic

The main SD card reader pins are on the blue outlined component labeled “SD CARD.” The power for the SD card reader is passed through a 3.3V regulator. A quadruple bus buffer gate (SN74LVC125APWR) is utilized to amplify the signals coming from MOSI, SCK, CS, and DO to drive a larger load. This design using bus buffer gate IC to transmit the SD card data will likely be replaced by simply using resistors and capacitors to limit the current going into and out of the SD card. The IC is not fully necessary, but it is currently part of the design. The SD card will most likely be sharing some pins with the ILI9341 display; as a result, this buffer has a three-state output that controls the flow of the signals. This then communicates to the ESP32 via more SPI pins. As seen on the bottom right, the bus that travels to the ESP32 schematic sheet has pins for input voltage (Vin), MOSI, MISO, CS, SCK, and ground. This resembles the way the display and its built-in SD card reader would interface with the ESP32. This “MicroSD_Pins” bus can be seen on the ESP32 schematic off to the left side.

Despite these being the primary subsystems that the team has worked on making schematics for, the main PCB will also contain terminals for all of the other peripherals. These include the stepper motor drivers, the cameras, the mechanical switches, and power. The next few sections will be dedicated to describing the design process of these other subsystems using block diagrams.

6.3 Motor Subsystem

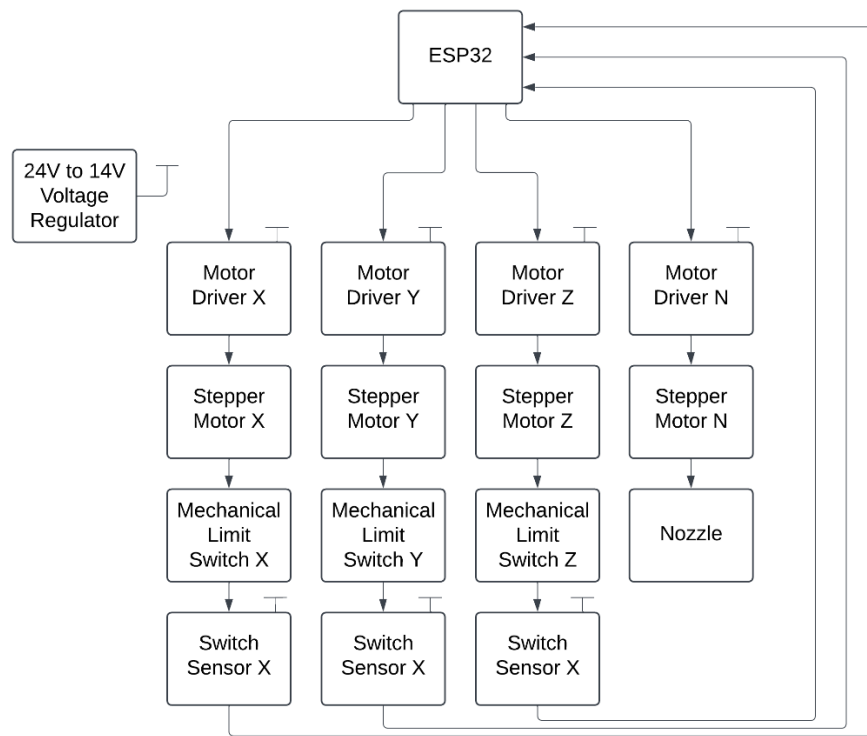


Figure 19: Motor Subsystem

This subsystem includes all of the things related to the stepper motors. The ESP32 will communicate with the X, Y, and Z coordinate stepper motor drivers. Those same drivers will be powered by the voltage regulator that is connected to the selected power supply. In addition, a fourth stepper motor driver will be utilized for dispensing purposes. All four of these stepper motor drivers will be connected to their respective stepper motors, which translate the electrical power to mechanical power. The mechanical limit switches and switch sensors for X, Y, and Z are only turned on if the solder paste dispenser is calibrating itself to determine the positioning of the dispenser. For example, when the dispensing process is about to begin, the ESP32 will communicate to the X-coordinate driver to drive the stepper motors until the nozzle hits the X-coordinate mechanical switch (which contains the switch sensor). Once the nozzle piece physically pushes the first X limit switch, the ESP32 will receive a signal from the switch sensor indicating that the nozzle has reached its “origin,” and this will shut off the X driver. This same process occurs for the Y and Z drivers and mechanical limit switches. Now the ESP32 is aware of the position of the nozzle before it begins to navigate to where the solder paste must be applied.

To control Stepper Motors, the ESP32 will be connected to the A4988 stepper motor drive through two main pins: the Step + Direction pin. This will allow the ESP32 to send the proper signals to the A4988 to control the number of steps to be executed. The A4988 will be connected to the same logic supply voltage from the ESP32 in order to achieve proper communication. The A4988 offers three micro-stepping pins that are active-high, this provides the SPD 5 stepping resolutions. Due to the precise nature required with printing, we will connect each line to Logic-High Node to achieve the maximum stepping resolution of 1/16. This will allow us to still achieve a full step by doing integer multiples of 1/16 (controlled by the software), while still allowing for the most precise movement.

The A4988 has a Reset, Sleep, and Enable pin to allow for proper configuration. The ENABLE pin will turn off all FET outputs when the voltage logic is high. Preventing any operation of the stepper motor. The Sleep pin will de-activate much of the ICs internal circuitry when set to a logic low level. This pin is intended to help minimize power of the driver and motor itself. To reduce the heat and power dissipated during non-operating periods. The Reset pin will set the IC's translator to a predefined home state and will turn off all outputs when set to a logic low level. Since we will assume the A4988 will always be enabled, we will simply let the ENABLE pin to be an open, keeping the internal IC always enabled. The reset pin will be wired to a logic high pin in order to always allow the IC from accepting step-inputs. However, due to the importance of power consumption on the SPD potentially being left in an "idle" state for long periods of time, the Sleep pins from all motors will be connected to a single GPIO pin allowing the ESP32 to activate the low-power mode of the A4988 when no print or movement is in progress.

The A4988 will require power directly from the COTS power supply to power the stepper motors themselves. The A4988 will allow an input voltage ranging from 8-35V. This is plenty of power to control the stepper motors especially with a small load. The current will be limited to not exceed the maximum 2 Amps per coil with proper heating.

The A4988 will connect to Stepper Motors through a long harness containing 4 separate pins. These pins will map two coils on the Nema 17 to provide a current through the motor's inductors. The length of the harness will need to traverse the distance to each motor respectively, with some extra length to provide less strain on the cables.

6.3.1 Nozzle

The motor driver and stepper motor for the nozzle is used for the actual dispensing process. Since the team has decided on using a stepper-motor driven system, it

will be the driving force to push the solder paste out of the tube and nozzle, onto the PCB. When the ESP32 properly aligns the nozzle piece with the X, Y, and Z motors, it will turn on Motor Driver N to drive Stepper Motor N which pushes the fluid out of the nozzle. The nozzle is a tapered nozzle of at least 25G to ensure a 0603 (imperial) SMD package size. As the team builds and tests the dispensing system, a higher gauge nozzle like 27G or 30G can be utilized to achieve a higher precision of SMD package size 0402 (imperial) or 0201 (imperial).

The tapered nozzle will allow for a higher flow rate as the diameter gradually decreases in size leading up to the tip. The team is looking into testing a pneumatic pump for the sake of either ruling it out or implementing it into the project. However, at this stage, the stepper-motor driven system will suffice in providing the precision sought after.

6.3.2 Preliminary Altium Schematic Designs

Now that the ideas behind the design have been expressed, screenshots with preliminary designs for the stepper motors will be shown below. The team is currently considering positioning the stepper motor drivers on their own PCB separate from the main PCB. The reason for this is to prevent having a single, clustered PCB. The stepper motor drivers can be placed on their own PCB which will have its own voltage regulator as seen in the subsystem block diagram. The two PCBs will then interface via terminals on each of them.

The schematic below from Altium Designer shows the A4988 stepper motor driver. The top left circuit in this schematic uses decoupling capacitors to stabilize and filter out noise the driver's power supply. The top right performs a similar task as it is used to stabilize the circuit's logic power supply. Considering one driver will supply power to a single stepper motor, OUT1A, OUT1B, OUT2A, and OUT2B all provide the DC power for the one stepper motor it is assigned. MS1, MS2, and MS3 are configured by the ESP32 to select the microstep resolution of the stepper motor. Using low and high voltages, there are five combinations that determine the resolution. The STP, DIR, SLP, and RST pins also connect to the ESP32, which controls the power states of the A4988.

A majority of the resistors seen in the design are there for current-limiting purposes. In addition, the capacitors are used for stability, reference, or filtering purposes between the pins of the A4988 and the microcontroller. This schematic has yet to be interfaced with the ESP32 schematic previously shown. Once the connections are made between the ESP32 and the A4988, the PCB design can begin. Traces and vias will be made to connect pins OUT1A to OUT2B to the stepper motor of choice.

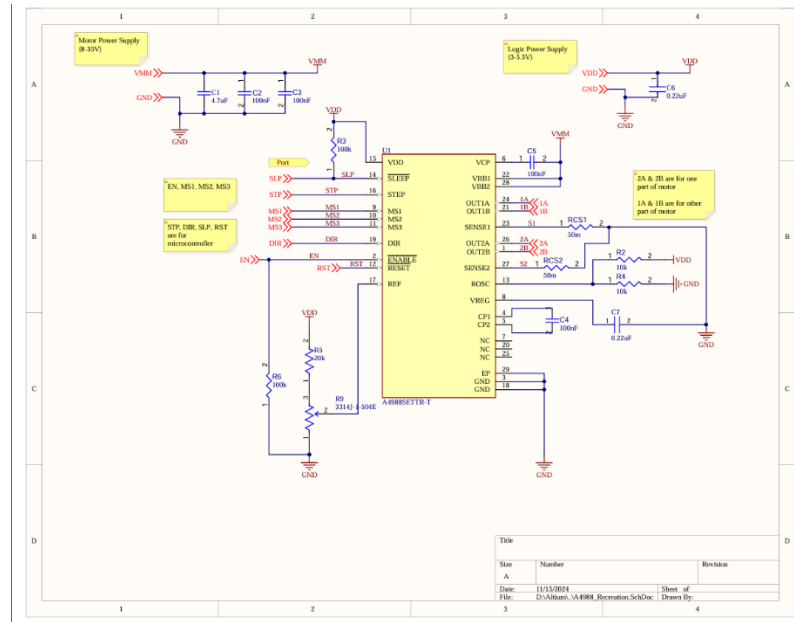


Figure 20: A4988 Stepper Motor Driver Schematic

6.4 Optical System

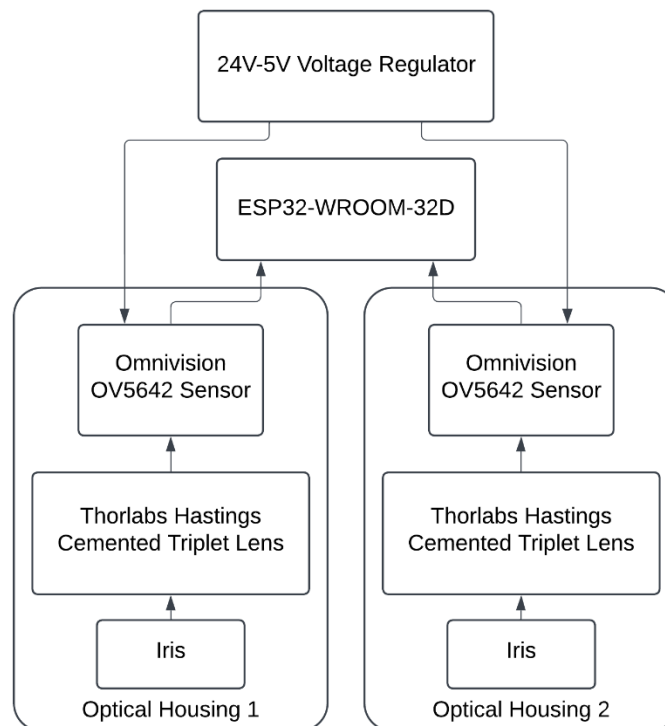


Figure 21: Optical Subsystem Diagram

The optical system will consist of an Arducam 5MP OV5642 SPI sensor, a Thorlabs TRH-040-A-ML Hastings cemented triplet mounted lens, an iris and an optical housing to hold all the parts aligned. The housing will be modeled using computer-aided design and manufactured using 3D printing. This is the same case for the iris, which is a parameter that can be adjusted in the future to modify light throughput and depth of field. The sensor will be mounted to the housing using screws. The lens will be mounted and will be friction fit into a slot in the housing. The iris will then be friction fit onto the front of lens. Having a friction fit allows us to securely attach the components to the optical housing while also allowing us to remove the components to iterate and test the optical housing. A 3D model of the first iteration of the optical housing is shown in the figure below in AUTODESK Fusion 360.



Figure 22: Cross-section of Optical Housing

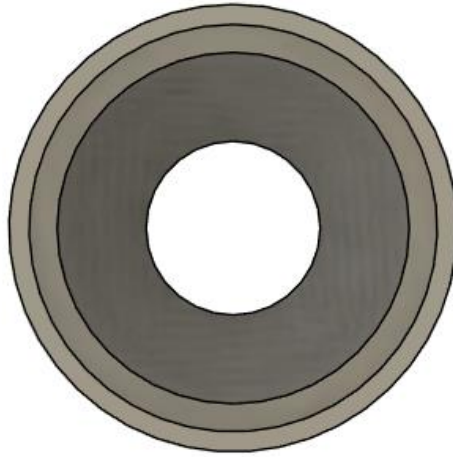


Figure 23: Top View of Optical Housing

The OmniVision OV5642 features built-in, proprietary image processing software which improves the overall quality of the images that are produced by the sensor. The sensor features OmniBSI pixels that offer good low light performance. This is important considering we are using a circular aperture to stop down our lens to achieve a sufficient depth of field, thus reducing the amount of light that comes into our system and hits our sensor. The sensor also features image processing that is dedicated to improving the depth of field of the camera. This, in combination with the depth of field we achieve, should be more than adequate for our imaging applications. To achieve a balance between depth of field and light throughput to the sensor, the diameter of the iris will be varied and optimized to achieve required specifications.

The Hastings cemented triplet lens is a finite conjugate lens that is optimized for magnification performance. For our case, we require magnification to create an image on the sensor that adequately covers the sensor. This is why we opted for the Hastings triplet rather than the Steinheil triplet, which is a triplet that is optimized for infinite conjugate imaging. We also opted for a triplet because we can get the best performance regarding aberrations.

The optical system design is shown below in Ansys ZEMAX OpticStudio. The lens is positioned such that we have optical magnification where the image area sufficiently covers the sensor and adequately covers our object area. The system's pupil size is set in the system explorer at a 3 mm diameter. This gives us proper imaging of the area and a sufficient depth of field. The required magnification

specification is obtained when viewing the image on a computer monitor on the website.

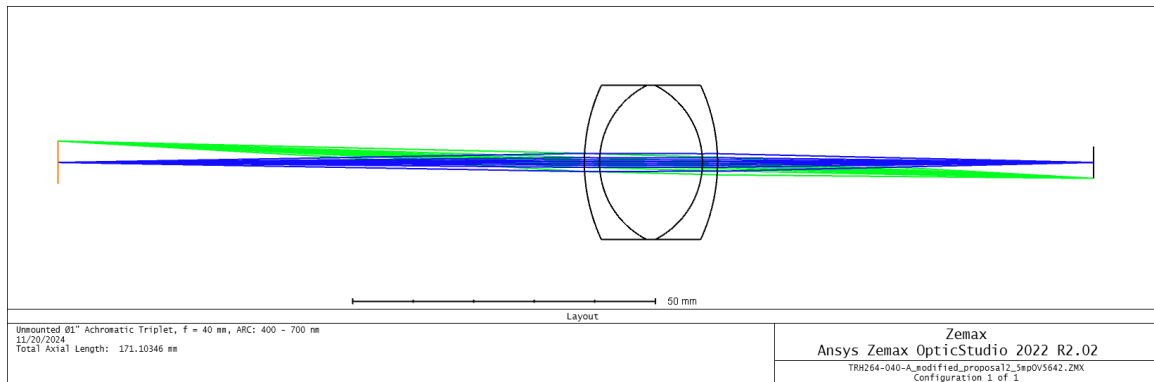


Figure 24: Optical Design in Ansys ZEMAX OpticStudio

These fully assembled camera modules will be around 10 cm in length. To image the area properly, the dispensing head will raise the modules to a specific height and a photograph is taken of the area of interest. The sensors in the cameras will communicate with the PCB using the sensor's SPI interface. The images will be sent to the web server for processing.

These two camera modules will have to be attached to the dispensing head on either side, and they must be aligned such that they are looking at the same 5 mm x 5 mm region, but from different perspectives. Increasing the width between the two cameras results in an increase in the achievable height resolution because we have an increase in parallax. However, the longer we make our baseline length, the farther the cameras must sit from the plate that holds the PCB. With the current design, the distance between the object and the lens is set to around 8.7 cm. If we want a minimum angle of 60 degrees, we need the distance between the cameras to be 8.7 cm. This would require us to position the lens of the cameras to a height of 7.53 cm above the subject for proper focusing. If we want to achieve a maximum angle of 80 degrees, we need the distance between the cameras to be 3.02 cm. This would require us to position the lens of the cameras to a height of 8.56 cm for proper focusing. This should be adequate distance to fit the dispensing head in between the cameras.

It is also important to achieve the set required specifications. Since the positioning of the cameras directly impacts the achievable resolution, it is important to find an ideal position for the cameras that will achieve the resolution in the optimal range for stereopsis, 60 – 80 degrees from the baseline, the line between the camera lenses. Since a longer length in the baseline leads to better height resolution, the

cameras will first be tested at the most extreme angle of 60 degrees. There will be a series of iterations before the optimal configuration is achieved.

6.5 Power Supply

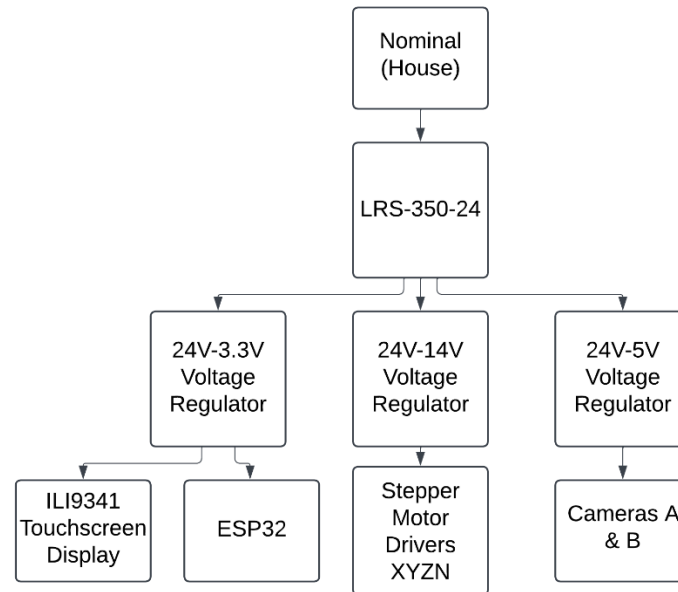


Figure 25: Power Subsystem

The power supply of choice is the LRS-350-24, providing a maximum of 24V at 14.6A (350.4W). This power supply will receive its source power from the nominal voltage (house). A three-prong power cord with exposed live, neutral, and ground wires will be used to connect the PSU to the wall. The three prongs will enter the outlet, and the exposed wires will be hooked up to the AC input of the LRS-350-24. There are three positive DC voltage terminals and three negative (or ground) voltage terminals for the PSU's output. Each of these will connect to a regulator as seen in the power subsystem above. The 24V to 3.3V voltage regulator powers the ESP32, ILI9341 touchscreen display, and other peripherals directly connected to the ESP32 like the SD Card reader. A 24V to 14V voltage regulator will be used to power the four stepper motor drivers and four stepper motors. Finally, a 24V to 5V voltage regulator will provide power to both sensors (OV5642) used for the optical system.

As seen in the LRS-350-24 datasheet block diagram, the PSU includes a filter, a switch for the user to determine whether 115/230V is being provided to the input, a rectifier, a DC-to-DC converter with the help of the PWM control, and a cooling fan with controls. On the left, I/P indicates the AC nominal (house) input voltage

that is being provided, meanwhile, +V and -V indicate the DC output voltage terminals that will connect to the voltage regulators.

The LRS-350-24 will provide enough power to run all of the other systems that rely on it. Since there are three positive DC voltage terminals and three negative DC voltage terminals, each one will be limited to providing only a certain amount of current. For example, the terminals that connect to the 14V regulator will be allowed to source at least 8A to power the four stepper motors. The terminals leading to the 3.3V regulator to the ESP32 and ILI9341 will source about 2A. The terminals leading to the 5V regulator to the cameras in the optical system will source about another 1 to 2A. There are more components that require powering than just the motors, ESP32, display, and cameras; however, the other parts do not consume as much power and can be considered more carefully when the system is being brought together and tested.

These power requirements should suffice for the current scope of the project and the current distribution might slightly change depending on any extra peripherals being added or power loss throughout the device.

Chapter 7 – Software Design

7.1 Software Overview

The software is the “driver” for the Solder Paste Dispenser. It enables the pieces of hardware to do the dedicated task that the project seeks to accomplish. Without the software properly running, there is merely just a set of hardware components unable to perform the functions needed. The Software will need to be implemented precisely in order to prevent bugs and un-predictable behavior to ensure the Solder Paste Dispenser runs smoothly.

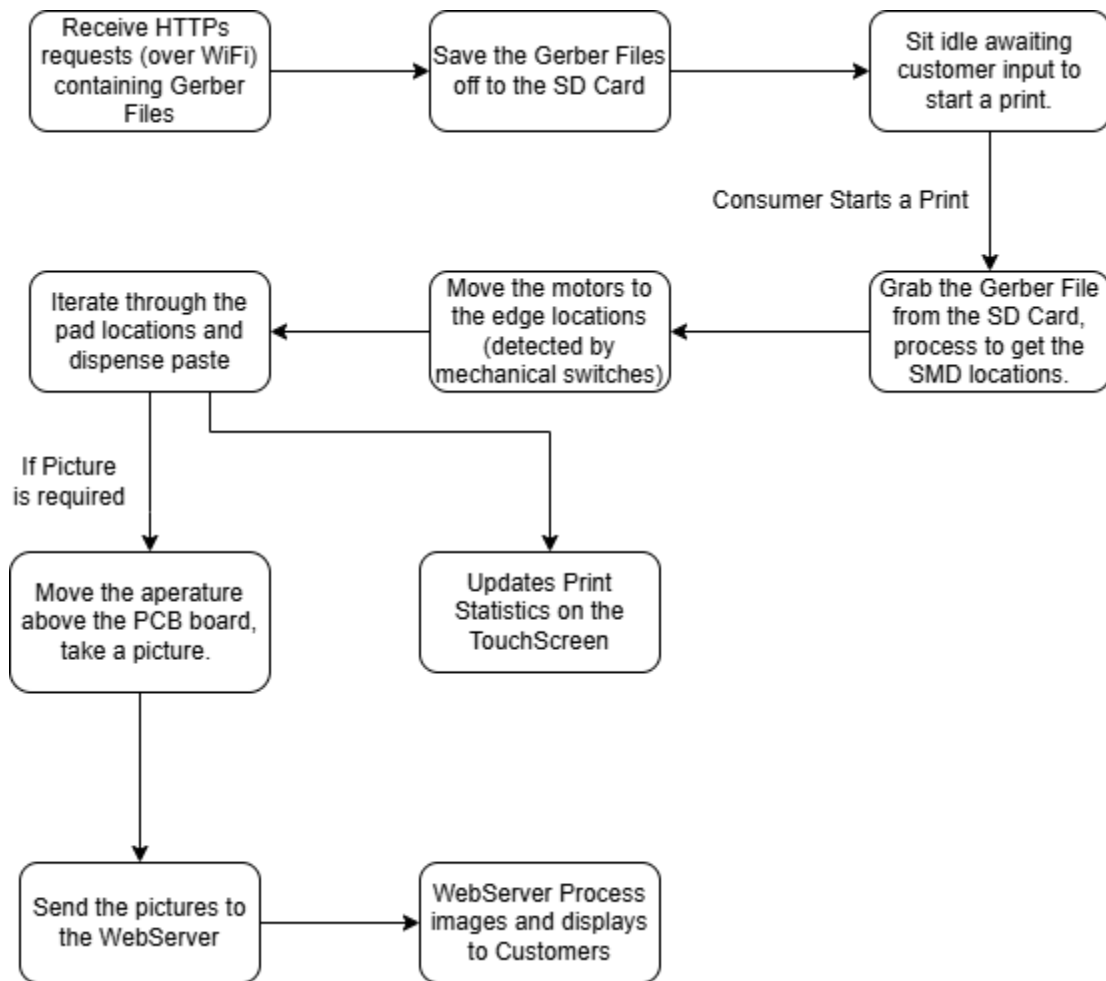


Figure 26: High-Level Software Process

The diagram above represents the high-level breakdown of the process in which the consumer will send the files and start a print. Starting from the moment the ESP32 receives the Gerber Files from the Web Server. Note during a print, the user will be able to force close the process and return to the normal “idle” state. In this idle state, the ESP32 will be constantly checking for either a touch input from the user or using an HTTP Get request.

7.1.1 Software File Hierarchy

The software will be written in the following hierarchy to ensure that the code base remains clean and consistent. By standardizing this structure it allows easier movement between different sections of the source code, ensuring that programmers know exactly where each file should be placed. It also helps with scalability as the source code grows each element and subsystem has a place to

easily go. Below is a figure showing the Software File Hierarchy for the Solder Paste Dispenser.

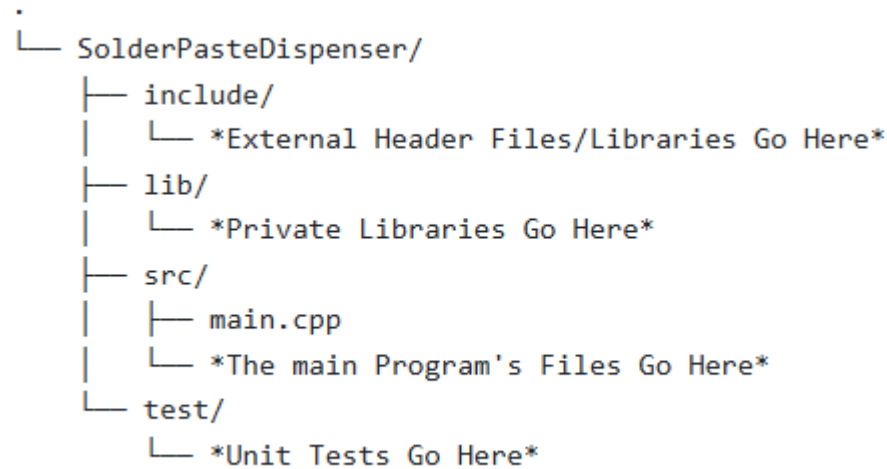


Figure 27: Software File Hierarchy

7.2 User Interfaces

The Users will be able to interact with the SPD through two main means: a website and a touchscreen. The touchscreen is the physical screen that will be located at the base of the SPD. The website will be hosted on an internal Wi-Fi network that the SPD is connected to. This will allow users to send files and receive pictures and updates from their devices. Using the website will allow users to send their Gerber Files wirelessly directly to the SPD. This reduces the time needed to save those files on a MicroSD card, which will need to be physically inserted into the SPD. Meanwhile, the touchscreen will be the main interface for controlling SPD's mechanical controls. This includes starting and stopping a print, and the basic setup required as a pre-requisite to printing.

The touchscreen will have a "Main Menu" which will display the status of the printer's SD card as well as have options for the other menus to select a file to start a print and to control the SPD manually. The "Manual Mode" menu will have controls to move the SPD's nozzle on the x, y, and z coordinates and manually print solder paste onto a PCB. The "File Selection" menu will show Gerber files that have been uploaded to the SPD which are held on the SD Card. From the "File Selection" menu the user will be able to select a file and start a print job. After a print is started, the file is converted to x, y, and z coordinates so the print can begin. After the file has been converted to x, y, and z coordinates, the user will be prompted to set up their PCB on the bed. A laser will shoot down from beside the

nozzle to where the PCB origin should be, and the user will have to adjust the PCB to the origin based on the laser then the user can press the start button which will begin the printing. When the print is started then there will be a “Printing Status Window” which will display the amount of solder paste pads that have had solder paste dispensed on and have had photos of the printed pads taken, as well as the number of pads remaining. This will give the users the ability to monitor the status of the current print for their PCB. There will also be a force-stop button that will immediately stop the print in progress. This is for safety, so users can stop printing early due to any potential malfunctions. After the print is over, the display will show a new screen saying that the print is complete and that the PCB can be removed. The menu will also have a button to return to the main menu where the process can be started over again.

Below are two prototype menus for the touch screen display. The first is a prototype for the main menu and the second is a prototype for the manual mode menu. This are great for getting an idea of what the menus could look like.

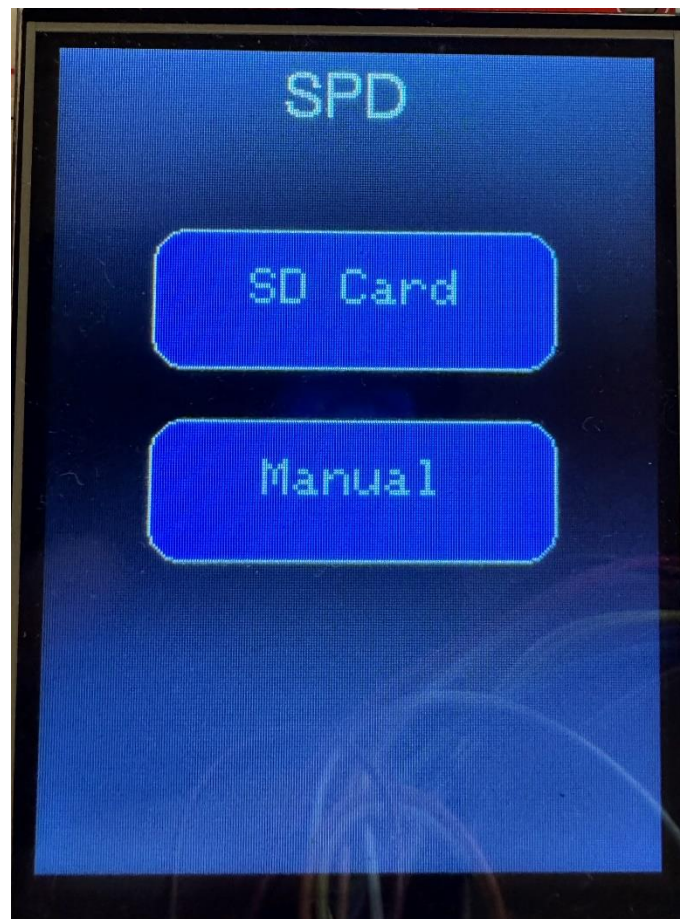


Figure 28: Main Menu Prototype

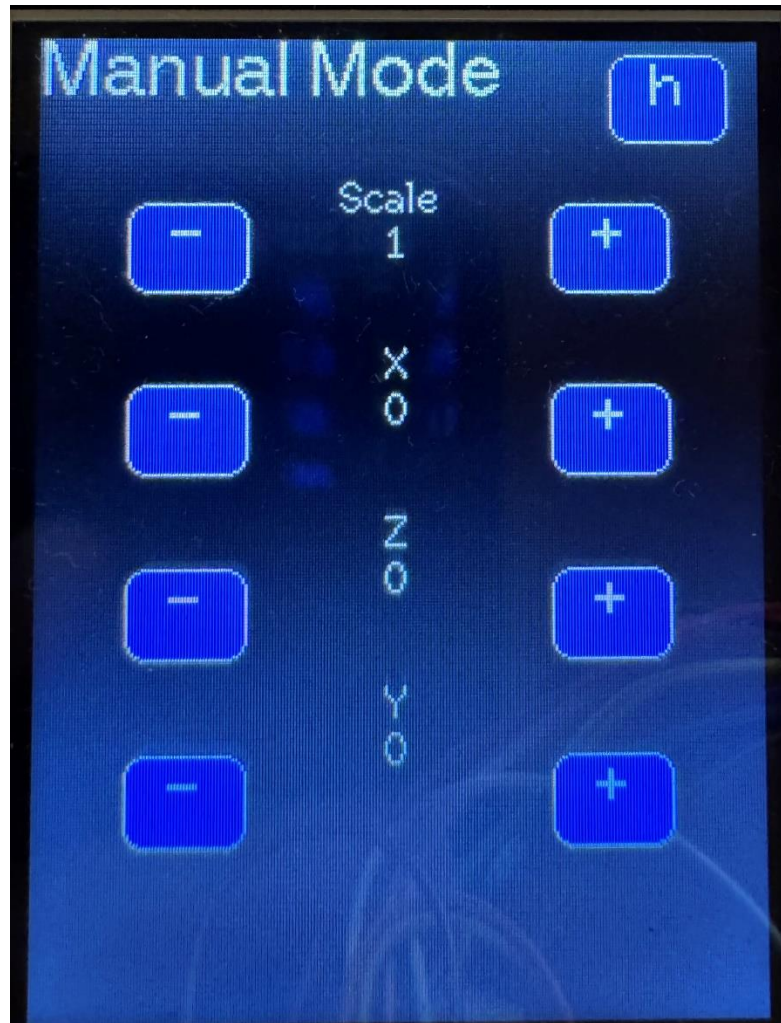


Figure 29: Manual Mode Menu Prototype

7.3 Class Structure

The Class structure of the software will prioritize re-usability across the project. Having a proper class structure will allow less repetitive code as methods/functions can be abstracted out. This section will go over the main classes that will be used by our microcontroller, encompassing the functionality that each class will deliver. Figure 27 depicts the overview of the main classes that will be developed to support the functionality of the Solder Paste Dispenser.

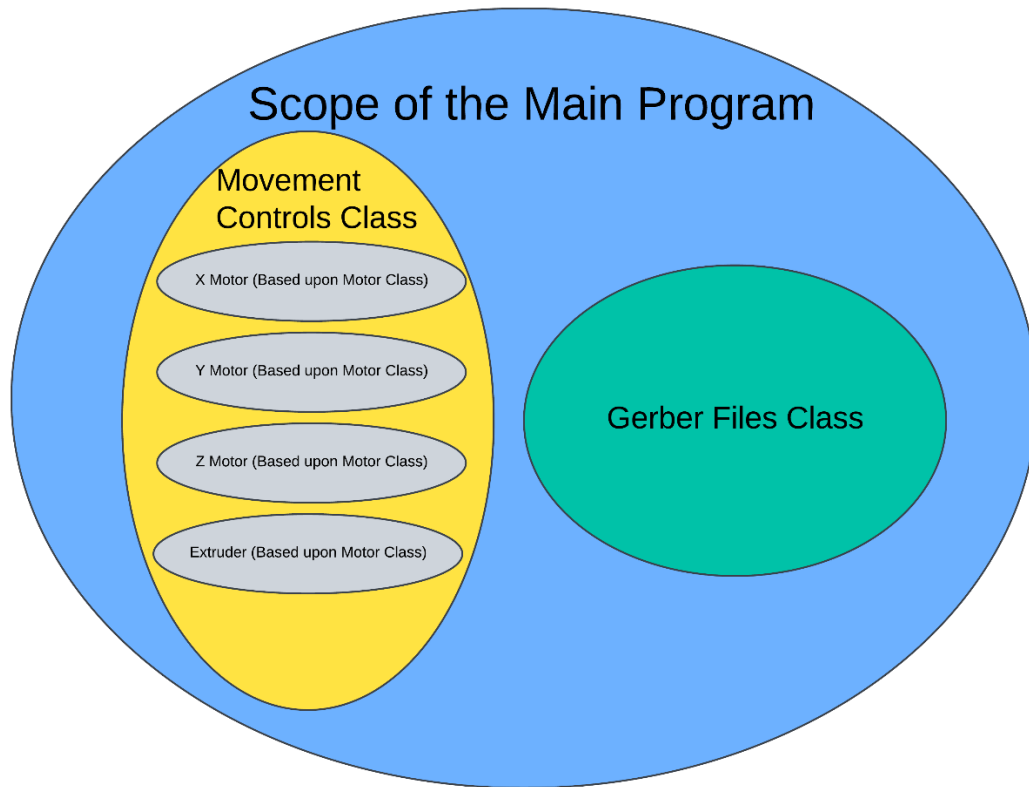


Figure 30: Class Overview

7.3.1 Class Requirements

Each class will be located within the “lib” folder for the project. The classes and their variables will be declared within a header file that can easily be imported to other files. The function bodies (all the content that makes the functions useful) will be in another cpp file. By using c++’s `#ifndef` and `#endif` calls we can ensure that there are no duplicated classes and methods to ensure the program will compile correctly.

7.3.2 Motor Controls Class

The first main class will be that of Motor Controls. Since the SPD will have a motor to control each of the three axes of movement: X, Y, and Z. Each motor will be responsible for moving its associated axis to the proper location. Since all the physical stepper motors and drivers are the same, this will allow us to easily abstract out the functionality into a common class. This class will include functionality for setting the speed and acceleration and moving it to a precise location. However, due to differences in how the motors are mechanically

connected to the printer, the class will need to be allowed a variable to configurable to translate each step into a movement in millimeters.

The Motor Controls class will also include the current location of the dispensing nozzle. This will be used to calculate the difference in position from the nozzle to each Solder Pad. From there we will be able to move the motors in the X and Y direction required to dispense paste. During normal operation the Z-axis will be calibrated by the user prior to printing. From there we will raise the dispensing nozzle's height while moving the nozzle in between each Solder Pad. Once the nozzle is located above the Solder Pad, we will once again lower the nozzle and dispense paste.

7.3.2 Gerber Files Class

The next main class will be for the Gerber Files. The main constructor for this class will take the file path to the Gerber File itself. From there the constructor will parse the Gerber Files and fill out the internal structures used to collect the information required to locate the Solder Pads. This class will contain a vector that is used to store the Solder Pad locations using a simple structure containing the X and Y locations. This vector serves as a dynamic array that will allow us to add coordinates as we read them. From there we will be able to sort the vector by coordinates that are closer to the origin. This will then allow us to use the vector as a "queue" structure in which we are able to grab the coordinates at the front of the queue. This will allow us to pop the coordinates in order from the closest to the origin. By processing our Solder Pads in this order, we minimize the amount of movement required to traverse the PCB and dispense the paste. Minimizing the movement is essential as it will allow the SPD to run quicker, while being more reliable.

7.4 Communication

The microcontroller will utilize a Wi-Fi connection to communicate with the backend of the Website. This Wi-Fi network will be hosted by an external device, allowing both the Solder Paste Dispenser, the Web Server, and client devices to be connected simultaneously. By hosting the Wi-Fi network on an external device rather than the ESP32, it reduces the load required for the ESP32. The microcontroller will await a HTTP request that will be utilized for transferring data from the Website to the microcontroller. The microcontroller will also be responsible for initiating HTTP to the backend to send pictures and status updates from the print to be displayed.

The microcontroller will have a main SPI line used for communication with the micro-SD card, the camera modules, as well as the touch screen. This reduces the

number of pins required to interface with the peripherals. The microcontroller will be responsible for enabling the chip-select (CS) pin to the peripheral it needs to communicate with at the proper time. The CS pin is an active low, indicating that a low voltage will lead to the peripheral being enabled. Since SPI will only allow communication between one peripheral, constant switching of the CS lines will be required to constantly poll for input on the touchscreen. Since the camera and micro-SD card lines will only be used in explicit situations, the default line to be active will be the touchscreen.

7.5 Computer Stereo Vision and 3D Reconstruction

Computer stereo vision involves extracting 3D information from two images of a scene captured from different perspectives. By using the baseline—the distance between the two cameras—we can determine the depth of points in the scene. This is done by matching corresponding pixels in each image and calculating the disparity between them, which can then be used to trigonometrically compute depth. Our camera system consists of two modules that will be mounted to the dispensing head. The lenses in the camera modules are separated by a baseline distance, and they are angled and toe-in to view the same region. To focus these cameras on the subject, the height of the dispensing head will be manually adjusted using the SPD's touchscreen interface. In the following paragraphs, we will discuss the approach that will be taken to produce 3D stereo reconstructions of the imaged PCB area.

The first step in our stereo system is image acquisition. To ensure best accuracy, image acquisition for each camera should occur simultaneously to avoid any kind of temporal misalignment. This ensures that the cameras take the image in the same lighting conditions and if there are any vibrations, the impact will be the same in both images. Following image acquisition, the images are then sent for processing.

To reduce the computational intensity and improve the accuracy of feature matching, the images will go through preprocessing. The images captured will be represented by matrices with each element corresponding to a pixel. These images will be in full color so each pixel will have three values describing the color of the pixel. For this reason, we will first convert the images to grayscale to rid of the unnecessary RGB (red, green, blue) information and replace it with a single value for intensity. This reduces the computational load and improves accuracy by making it easier for feature matching algorithms.

After converting to grayscale, the images will be rectified using image rectification. Image rectification is a process where transformations are applied to a pair of stereo images to align corresponding points in the images so that they sit in the same row. This is important because it simplifies and significantly improves the accuracy of feature matching. Furthermore, image rectification ensures consistency between the two images. Any kind of mechanical misalignment between the cameras or distortions in the image will be corrected for. This is crucial for accurate stereo matching.

Following image rectification, the pair of images is ready for feature matching and finding the corresponding pixels. Out of all the steps, this is typically the most intensive computation that must be done. This is because the software must search the images using a kernel and then do a correlation between the kernels to find where the images match. There are a variety of methods that can be used to do feature and pixel matching, and they all vary in computational intensity and speed. Considering that the stereo reconstruction is not going to be live and in real-time, we have the flexibility to use computationally intensive methods to ensure best accuracy. Our goal is to produce an accurate 3D reconstruction of the imaged area. Our application is PCB inspection, so it is critical that the 3D point cloud that is produced has enough density in points to accurately capture defects like unwanted bridging between two solder points. In the next paragraph, we will compare the various methods for pixel and feature matching.

The first method utilizes the Scale-Invariant Feature Transform (SIFT) with the Fast Library for Approximate Nearest Neighbors (FLANN), both the algorithm and the library were developed by David Lowe. SIFT works by using Gaussian blurring at different blur intensities and compares regions with unique patterns in intensity changes to find matching features. It is particularly useful for feature matching. The SIFT algorithm is used to find distinctive key points, like corners, between a stereo image pair and then assigns a descriptor, usually a vector describing the feature's position. [99] Then FLANN can be used to organize these generated descriptors and match features between images by finding the nearest neighbors in descriptor space. This method is particularly useful for general feature matching, not specific pixel matching. It is useful for computer vision tasks like object detection. In terms of computational intensity, it is moderate. [100]

The second method involves using the Oriented FAST and Rotated BRIEF (ORB) algorithm in conjunction with FLANN. ORB is a fast, rotation-invariant feature detector and descriptor. It is an algorithm that combines Features from Accelerated Segment Test (FAST) for key point detection and the Binary Robust Independent Elementary Features (BRIEF) algorithm for generating descriptors. ORB is faster

than SIFT but provides the same sparse point cloud. It is useful for quick object detection. Regarding computational intensity, its relatively low. [101]

The third method is using StereoBM in OpenCV. StereoBM is a class for computing stereo correspondence using a block matching algorithm. Disparity is then calculated by using whole blocks of pixels rather than individual pixels. StereoBM is useful for images that are rectified and provides better point-cloud density as compared to the previous methods. It is more computationally intensive than the previous two. StereoBM works by dividing both images into small blocks, and then compares those blocks to find the best match. Then disparity is calculated for each block by using the displacement of the blocks in each image. There are some challenges though, the algorithm struggles in areas with poor texture or repetitive patterns. [102]

The fourth method utilizes another class in OpenCV that is referred to as StereoSGBM. SGBM stands for semi-global block-matching. This technique is like StereoBM, but StereoSGBM can produce even denser point clouds and is computationally intensive. StereoSGBM is similar to StereoBM in that it divides the images into small blocks and matches those blocks. However, instead of looking at one block at a time, the displacement is considered across the entire image. This results in a finer point cloud and includes smoothness in the point cloud. [103]

Each method will be considered and tested, but since we want a dense and information-rich point cloud, we will begin testing with StereoSGBM. After corresponding features and pixels have been mapped, we can find the disparity map for the images by calculating the difference between the horizontal positions of each matched pixel. Using this disparity map, we can use triangulation to calculate the depth map. This depth map then can be used to create a 3D point cloud that accurately represents the area of interest. [104]

Photo processing for the camera and stereoscopic system will be handled by the Web Server. Photo processing will be done utilizing the OpenCV library. Images sent from the cameras will be labeled as a pair. This pair of images will be taken, converted to grayscale, and optical distortions will be removed by using the camera's characteristics. These images will be rectified using image rectification. Following rectification, the images are ready to be processed to produce the disparity map by pixel matching. Pixel matching will be done by using Stereo Semi-Global Block-Matching because it provides sufficient point density for our application. After the pixels have been matched and disparity has been calculated, we use the physical positions of the cameras to calculate depth. For each pixel

matched, depth will be assigned, and a 3D point cloud is produced that the user can then export. The SPD will automatically take photographs of a pad after solder paste has been dispensed on it and the website will provide the photographs, as well as 3D reconstructions of the pads. As a stretch goal, we would like to have a real-time 3D point cloud output on a visualizer on the Website.

Chapter 8 – System Prototype Construction

8.1 Overview of System Construction

The mechanical structure of the Solder Paste Dispenser will be inherited from a Creality Ender 3 printer. This limits the amount of construction required and allows focus to be on the features being implemented. There are a few main features that will be stripped and constructed to modify the existing hardware to perform the task specified. The printing nozzle will be stripped, and the backplate will be used to mount the extruder and cameras. The touchscreen and PCB that come with the ender 3 will be removed and replaced with our custom PCB and touchscreen hardware. It will also require the printing bed to be modified to hold the PCBs as well as determine the PCBs location relative to the nozzle on startup.

8.2 PCB Fabrication

The PCB will be ordered from JLBPCB following completion of the design. The PCB design will include proper labeling on the silk screen layer to provide better clarity during fabrication. Once acquired, solder paste will be applied to each of the Solder Pads, and the System Mount Devices will be positioned. Following that a re-flow oven will be used to solder the components to their location. Upon building out the PCBs visual inspection under a micro-scope will be used to ensure continuity between each device's pins and its corresponding surface mount pads. A Digital Multi-Meter can be used to test continuity between traces and test-locations built into the PCB.

8.3 Micro-SD Card Preparation

All Micro-SD cards used with the Solder Paste Dispenser will need to be formatted prior to use. Each Micro-SD card will be connected to a device and formatted to "Fat32" prior to being connected to the housing on the PCB. The ESP32 on the PCB will not be required to format the Micro-SD card and will assume it has already been properly formatted. Failure to properly format a Micro-SD card may result in errors while trying to operate the Solder Paste Dispenser.

8.4 PCB and Touchscreen Enclosure

A custom enclosure will be designed, and 3D printed following the completion of the PCB design. It will serve to protect the PCB while keeping a professional presentation. It will allow the PCB to be mounted into the enclosure through screw-holes, and allow the touchscreen to be mounted, facing towards the users for easy access. It will have gaps in the enclosure to allow the Micro-SD card to be easily removed and replaced. It will also allow for easy cable management to the harnesses required to connect to components that are positioned on other parts of the mechanical system. Each harness used should be easily able to disconnect allowing for the PCB and sub-assemblies to be easily tested and troubleshot.

8.5 Extruder and Camera Mounting

Following removal of the printer nozzle and heating assembly of the Creality Ender 3, a custom mounting piece will be created in order to assure proper mounting of the Solder Paste extruder and Cameras. Due to the nature of the stereolithography system, each camera will need to be precisely placed and angled towards the point of interest. This custom mounting piece will be 3D printed and will allow our custom pieces of hardware to be easily installed to the pre-existing nozzle backplate on the Ender 3.

8.6 Prototype Construction

Each sub-assembly will be initially prototyped utilizing a bread board and an ESP32 Development Kit that utilizes the ESP32-Wroom. Each piece of additional hardware for the sub-assembly will be connected to this setup to allow for prototyping and testing of the software. By utilizing a breadboard, we enable easy connectivity to testing equipment such as oscilloscopes and multi-meters to allow for easier troubleshooting during development. External power supplies will be used during the prototype stage to power each sub-assembly.

8.7 Optical Housing

The optical housing is a critical part to get right since it impacts the alignment of the optical components and the final quality of our camera module. It is important to experiment with different mounting methods to ensure that components fit securely for testing. For quick prototyping and iteration, we will utilize additive manufacturing processes.

Prototypes for the optical housing, which will hold the lens, sensor, and iris, will be manufactured using 3D printing. This approach provides the flexibility to rapidly iterate on the design, allowing adjustments to be made quickly using computer-

aided design (CAD) software. 3D printing not only enables us to tailor the housing to meet specific dimensional and alignment requirements but also allows us to explore various configurations that optimize the positioning and stability of the optical components. The ability to produce detailed prototypes in-house minimizes the need for outsourcing, reducing lead times and associated costs. Additionally, 3D printing allows for quick implementation of design improvements based on experimental feedback, ensuring that the final optical housing achieves precise alignment and functionality.

It is also important to test the characteristics of the camera. Since we are imaging a small region of 5 mm x 5 mm, it is critical that we have a way to characterize the flaws in our fully developed camera modules. One current method that is being considered for use is using an ink printed, black and white grid that fits in the 5 mm x 5 mm object area. This should allow us to extract the camera parameters for image correction when we do the image processing.

Chapter 9 – System Testing and Evaluation

9.1 Software Testing

9.1.1 Unit Tests and End-to-End Tests

For software testing, two techniques can be employed to ensure proper software functionality. The two techniques are unit tests and end-to-end tests. Both have their pros and cons, which is why both are needed to take advantage of both their upsides and to know the software is working properly and fully integrated.

Unit tests create isolation for function testing and make sure each function is producing a desired output within the code. A nice feature about unit tests is that they are quick to run and are great to run after adding more functionality to the overall program. Unit tests do miss the big picture of the fully integrated design testing because of their isolation which brings the need for end-to-end testing. End-to-end testing is unfortunately slower because it relies on mostly manual testing but is needed to test all the software integrated with itself and with the hardware components.

A thorough process can be made with unit tests to ensure the proper reliability and performance of the software components. Sub-systems will have unit tests written utilizing PlatformIO's infrastructure. PlatformIO automatically creates a folder to contain unit testing and allows multiple ways to run them. Unit testing will enable us to break apart key components required for the SPD to operate properly. When

breaking apart these components we can write tests for each component's functionality.

Unit tests are to be employed for the Gerber File conversion software, and for the backend portion of the website which handles sending Gerber Files to the ESP32 and receiving photos taken by the optical system which are transmitted by the ESP32. An example of a unit test is that during the parsing of a Gerber File, we want to ensure it parses all files properly. We can create examples that are passed on to the functionality we have of processing Gerber Files and check the results compared to the expected results which could be an expected successful execution or failed execution. This allows us to ensure that the functionality remains consistent and accurate despite changes to the code such as re-factoring or additions of functionality.

Individual unit tests will be created under the "test" folder within the project's directory. For each key component/functionality, a unit test can be written. The file name for the unit test shall match that of the method/function under test. When committing to the repository unit tests shall be run to ensure key functionality remains intact. When a developer writes a new feature, they shall also write a unit test to check for proper functionality.

End-to-end tests will be needed to confirm the front end works correctly for the user and to ensure the experience from the front end is seamless and intuitive. Also, the end-to-end tests will help ensure that proper results between different functionalities in the code perform as expected and that the software with hardware integration works as intended. For example, the end-to-end tests can be used on the touchscreen display and website front end to make sure buttons are working and that the correct information is being displayed.

9.1.2 Gerber File Conversion

The Gerber File conversion functionality exists on the ESP32 because it takes files that have been written to the SD Card and makes them into usable parameters of x, y, and z coordinates that the ESP32 can use during the printing process to move the stepper motors efficiently. Unit tests can be used here to ensure the files are properly converted into the desired output and the unit tests can be run before uploading the code to the ESP32 for efficiency. The unit tests will have various Gerber Files passed through the function and at the end be checked by what we have predetermined what the results should be.

9.1.3 Touch Screen

The touch screen will allow the user to choose different files uploaded to print from, help the user navigate the process of completing a print, and enable the user to control the printer manually if necessary. The best tests to employ are end-to-end for the touch screen. To test the touch screen will systematically go through each part of the user interface step by step, ensuring each button is pressable and performs the correct operation.

9.1.4 Website

The website has a front end and a back end, so tests need to be chosen accordingly. For the front end, end-to-end tests will be used to ensure the correct information is displayed and that buttons perform as intended. On the backend which will communicate to the ESP32, unit tests can be used to ensure proper communication is transmitted and received.

9.1.5 Stepper Motor Control

The code for controlling the stepper motors exists on the ESP32 and controls the motors' movements which move the nozzle into a desired position. End-to-end testing will need to be utilized to determine if the coordinates passed to the system are moving the motors so the correct position for the nozzle is realized.

9.1.6 Image Processing

For image processing, we want to ensure that we can generate an accurate stereo reconstruction of the area of interest with enough point density. This ensures that the user can utilize quality stereo reconstructions to analyze the quality of solder paste dispensing. It is very unlikely that the software will be developed in one go so it is necessary to test and characterize the performance of the software and find where accuracy and point density can be improved. It is also important to ensure that the software is reliable and that it produces outputs of sufficient quality for all kinds of scenarios that will be encountered in our applications.

Software testing will consist of analyzing the performance of each step by using test images obtained from the fully assembled cameras. To ensure the software works for our specific applications, software will be developed alongside the cameras. For our first iteration, rather than building both cameras at once, we will use a single assembled camera module that is tilted at the specified angle, and it will be mounted on a rotating mount. This setup will be used to acquire the first stereo test images that will be used for testing the processing. With these test images, we can run our software. Then, issues with the quality of the output will be assessed and routes for improvement will be considered. It is likely many iterations

of the software will be produced and to ensure we stay organized, there will be versions of the software.

9.2 Hardware Testing

Hardware testing is crucial to ensuring all hardware is made to spec. During manufacturing, there can be mistakes or small unintended variations in a PCB or IC circuit that could cause issues from short circuits or open circuits which can cause parts of the circuit to either be given too much power and then destroyed or given no power and not turn on whatsoever.

There are a multitude of ways of testing hardware. A continuity test can be employed which will show whether two parts of a circuit are connected or not connected. A voltage test can be performed when power is applied to the circuit to see if the correct voltages are being read at the right nodes of the circuit. A current test can be done by checking in line of the wire if the correct current is existing through the wire.

9.2.1 PCB

The PCB made by our team will need to be tested extensively to ensure proper function, that no manufacturing errors have happened, and that no design flaws exist that prevent full integration of all devices. Our PCB will have easy-to-access test points on top of the PCB to allow for fast and easy testing of voltages on nodes and continuity between nodes and where they connect to IC chips, resistors, or capacitors which are soldered on the PCB.

9.2.2 Touch Screen

The touch screen hardware testing will consist of testing the voltages of the pins on the display module to ensure that the correct power is being delivered to it. The pins to focus on will be ground, the input voltage the device needs to turn on, and the backlight. The ground should measure zero voltage. The input and the backlight should measure the same at 3.3 volts. For the rest of the pins and the ones mentioned already, a continuity test can be employed to ensure connection to the PCB and ESP32.

9.2.3 Stepper Motor and Stepper Motor Driver

The stepper motors and stepper motor drivers work in tandem. There are three of each, stepper motors and stepper motor drivers. Each pair, stepper motor, and its connecting stepper motor driver will be tested separately under the following tests. There should be continuity for the corresponding pins from the stepper motor to

the stepper motor driver and then to the ESP32. The stepper motor driver should have an input voltage in the range of eight to thirty-five volts. The stepper motor should not exceed an input voltage of twelve volts. Both device's ground voltage should be zero.

9.2.4 Optical System

The physical optical system will be developed iteratively, and the modules should be easy to take apart to fit different housing prototypes. We start with a single camera assembly and develop the mounts that will attach to the dispensing head. First, the mount will work such that the camera can be rotated around the dispensing head so we can test software alongside hardware. The single camera assembly will be physically optimized to improve alignment issues and other challenges. Then a second identical camera module will be printed and assembled. Ideally, the final version of the camera modules will be rigidly attached to the mount. The mount will also probably feature an illumination element to light up the PCB for better imaging. The camera modules should also not sit lower than the tip of the dispensing head as it would interfere with dispensing.

It is also important to consider the requirements for the resolution of the measured heights. We require a resolution 10 μm . To ensure we can achieve this, we must optimize the physical positions of the cameras. Increasing the baseline distance between the cameras is great for increasing the resolution because we get a bigger displacement between the images. However, since our image area is fixed and both cameras need to image the same area but from different perspectives, the baseline length impacts the angle of the cameras significantly. A balance between baseline length and camera angle will need to be set so that we achieve our required height resolution.

Chapter 10 – Administrative Content

10.1 Budget and Financing

Component Description	Quantity	Cost per component	Cost Sum
ESP 32 MCU	1	\$8	\$8
Touchscreen Display	1	\$25	\$25
Stepper Motors	3	\$20	\$60
Motor Drivers	3	\$10	\$30
Power Supply	1	\$25	\$25

PS Regulator	1	\$12	\$12
Cameras	2	\$40	\$80
Optics	2	\$111	\$222
PCB	1	TBD	TBD
		Total Cost:	\$462

Table 19: Budget and Financing

*The 3D printer which the internal circuitry needs to be rebuilt completely has been donated to the team for this specific project. The cost is not provided in the table above.

10.2 Project Milestones

The milestones mark important objectives that our team needs to reach to complete this project on time. Staying on target with persistent planning and work will keep us on track. We plan to hit the ground running by starting to test and prototype earlier than needed to run into unknown issues and solve them sooner rather than later.

Initialization Phase				
Milestone	Description	Start Date	End Date	Duration
Group Formation	Bring the group together and meet our project sponsor	08/19/24	08/26/24	1 Week
Communication Tools	Group meeting to decide on tools to track tasks and stay organized	08/26/24	09/02/24	1 Week
Committee Formation	Reach out to faculty to form our committee	08/26/24	09/06/24	2 Weeks
D&C Paper	Complete the first 10 pages of the paper	08/26/24	09/06/24	2 Weeks

60 Page Paper	Complete the first half of the paper	09/06/24	10/25/24	7 Weeks
Final Paper	Finish and finalize the entire paper	10/25/24	11/26/24	5 Weeks

Table 20: Initialization Phase Milestones

Production Phase				
Milestone	Description	Start Date	End Date	Duration
Component Selection	Determine components for the project	09/09/24	11/26/24	11 Weeks
Gerber file software	Convert Gerber Files to x, y, and z coordinates	11/11/24	02/10/2025	13 Weeks
Stepper Motor Software	Take x, y, and z coordinates and move motors accordingly	11/11/24	02/10/2025	13 Weeks
Screen GUI software	User interface to start a print job or manually move printer motors	11/11/24	02/10/2025	13 Weeks
PCB Design	PCB to supply power and integration for hardware components	11/11/24	02/10/2025	13 Weeks
Optical Inspection System Design	Design and assemble optical inspection system.	11/11/24	02/10/2025	13 Weeks
Optical Stereoscopy System	Program image processing to produce 3D representations of target areas.	11/11/24	02/10/2025	13 Weeks

Integrate and Test	Ensure components work together and correctly	02/10/2025	03/10/2025	4 Weeks
Final Design	Fully function design complete and ready for usage	03/10/2025	04/10/2025	4 Weeks

Table 21: Production Phase Milestones

10.3 Work Distributions

Work Distributions	
Name	Tasks for Project
Nathan Boucher	Code to take XYZ coordinates and translate to stepper motors movement and dispensing, Part of Code to convert Gerber Files
Mikell Alfonso	PCB design and creation, PCB design for stepper motors
Elizar Tsymlyakov	Optical System Design and Image Processing Software for Stereoscopy and 3D reconstruction
Edward Weir	Code for Display GUI, Part of Code to convert Gerber Files to usable information for SPD

Table 22: Work Distributions

Chapter 11 – Conclusion

In conclusion, SPD gives a solution for dispensing solder paste on custom PCBs in an automated and easy process for any personal project with a custom PCB. Our project developed can help engineers with personal projects that require a custom PCB an easier and automated process to place solder paste efficiently and seamlessly with the SPD.

The process for users starting at the website allows users to quickly upload their Gerber file to the SPD for their PCB to begin the printing process. Then the user can interface with the touch screen to select their file to begin the dispensing of solder paste. After the user has selected their file and the PCB is placed on the bed the SPD handles the rest. The SPD then converts the Gerber file into x, y, and z coordinates to move the nozzle of the SPD to each pad on the PCB for precise dispensing of solder paste, and after each pad has solder paste dispensed on it, the optical system takes magnified photos of each pad with the solder paste on it. This allows the users to ensure the quality of the solder paste dispensed on each pad.

This paper shows the documentation and research of the development of the SPD. By development of the SPD, solves the problem of applying solder paste in an automated fashion for consumers with custom projects. It also expands on existing designs by incorporating an optical system to ensure the quality and reliability of solder paste dispensing. The SPD can hopefully be a benchmark for continued innovation on consumer-focused automatic solder paste dispensers.

Appendix

Appendix A – References

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