
Senior Design 1

Midterm Milestone Report

Money Sorting Machine



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Group 19

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Chapter 1 – Executive Summary

The efficient handling and sorting of currency is a critical task in banking, retail, and other industries requiring precise organization of cash. This project focuses on the development of a machine capable of orienting and aligning currency bills uniformly, regardless of their initial state, and outputting them in a neatly stacked format for seamless handling, storage, or ATM loading. Designed to operate with minimal user intervention, the machine will feature an intuitive interface for setup and monitoring, enabling ease of use.

To enhance its functionality, the machine aims to achieve several stretch goals, including the ability to accept mixed denominations and sort them by value, handle multiple currencies for international applications, and provide users with customizable sorting options via an integrated LCD screen. This added flexibility would allow users to select specific bill orientations, such as all bills facing up or heads facing forward, tailored to operational requirements.

The design and implementation of the machine are guided by key objectives, including determining an optimal mechanism to detect and adjust bill orientation through advanced sensors and actuators, minimizing the risk of jams or errors by accounting for variations in bill characteristics, and developing a user-friendly interface with alerts for errors, maintenance, or completed operations. Rigorous testing under varied conditions will ensure the machine's efficiency and reliability, even with mixed bill states.

This document details the design process, including the selection of key components, development of a robust sorting mechanism, and the integration of user-centric features. By addressing these goals and objectives, the project aims to deliver a high-performance machine that sets a new standard for currency handling while offering scalability for future enhancements.

Chapter 2 – Project Description

Before delving into the details of system components and implementation, this chapter provides an overview of the design considerations, constraints, and methodologies applied in the project. The system design process establishes the framework within which different subsystems interact to achieve the overall project objectives. Key decisions regarding architecture, materials, and integration strategies are discussed, ensuring a comprehensive approach to development.

2.1 Project Background and Motivation

The financial systems in cities, states, and countries worldwide rely on sophisticated machines to handle their currency efficiently and reliably. These machines play a critical role in reducing human error and maintaining security across various financial operations. From counting bills to identifying counterfeit currency, these tools streamline processes that would otherwise be time-consuming and error-prone. In some countries, the security of paper currency is taken to such extremes that even slightly torn bills are considered invalid and must be exchanged. While this level of scrutiny might seem excessive, it underscores the importance of ensuring the integrity of currency in circulation.

In contrast, the banking system in the United States follows a different set of guidelines. While torn bills may still be acceptable for transactions or deposits, banks enforce several organizational requirements to maintain efficiency and accuracy. One such requirement is the proper orientation of bills during deposits. Bank tellers are trained to ensure that all bills are neatly aligned, facing the same direction and orientation, before being processed. This seemingly minor task can be surprisingly time-consuming, especially for deposits involving large sums of cash, and it often requires meticulous manual effort. Consequently, this process may lead to longer wait times for customers, particularly during busy hours.

To address these challenges, many banks have introduced Automated Teller Machines (ATMs) that allow customers to make cash deposits without waiting for a teller. However, these machines often require customers to pre-orient their bills before inserting them, transferring the organizational burden from the teller to the customer. While this innovation has improved convenience, it still leaves room for inefficiencies and frustrations for users who are unfamiliar with the requirement or struggle with large deposits.

Engineers and financial institutions are continually seeking ways to improve these systems. Their goal is to enhance operational efficiency while also delivering better customer service. Advancements in technology, such as automated currency sorters and deposit machines capable of handling misaligned bills, represent significant steps forward. These innovations not only reduce the workload for bank staff but also improve the overall banking experience for customers by minimizing wait times and simplifying transactions. As these technologies evolve, they promise to revolutionize how financial systems handle currency, balancing the need for security, reliability, and user convenience in an increasingly fast-paced world.

2.2 Objectives and Goals

The main idea of this project is to build a communication tower and mirror tower to supply the rovers with a mesh communication network and sunlight for solar charging. Some of the main goals and objectives are listed below.

Goals:

1. The machine will be capable of orienting and aligning currency bills to ensure uniform direction and orientation, regardless of their initial state.
2. The machine must output bills in a neatly stacked format, ready for further handling, storage, or ATM loading.
3. The machine will operate with minimal user intervention, featuring an intuitive interface for setup and monitoring.

Stretch Goals:

1. The machine is capable of accepting mixed denominations and sorting them by value while aligning the orientation.
2. The machine is designed to handle multiple currencies, making it suitable for international use.
3. The machine incorporates an LCD screen that allows users to select the desired bill orientation (e.g., all bills facing up or down, heads or tails) before processing, providing customizable sorting options for different operational needs.

Objectives:

1. Determine the optimal mechanism to detect and adjust bill orientation, including sensor types and actuator designs.
2. Design the machine to minimize jams or errors, considering factors such as bill thickness, material, and size variations.
3. Develop a user-friendly interface and system alerts to notify operators of errors, maintenance needs, or completed operations.
4. Test the machine's efficiency and reliability under various conditions, including mixed bill states, to ensure robust performance.

2.3 Features and Functionalities

This high-performance machine is meticulously engineered with nine essential features, each carefully designed to enhance its efficiency, reliability, and ease of use. These features work in harmony to ensure seamless operation, from the moment a bill is inserted to the final stage when neatly stacked bills are ready for collection.

2.3.1 Input Mechanism

- The machine is equipped with a specially designed input tray that allows users to load a stack of bills effortlessly. Once placed into the tray, the machine's precision feeding system carefully picks up each bill one at a time, guiding it smoothly into the internal processing system for analysis. This ensures a steady and controlled intake, preventing jams or misfeeds.

2.3.2 Scanning Mechanism

- As each bill moves through the machine, it passes through an advanced scanning system that carefully inspects its features. This scanner plays a crucial role in identifying the bill's orientation. By utilizing high-speed optical scanning technology, the system ensures that each bill is processed with accuracy and efficiency.

2.3.3 Flipping Mechanism

- If the scanning system detects that a bill is facing the wrong side up, the machine's intelligent flipping mechanism is activated. This automated feature precisely rotates the bill to its correct position before moving it forward for further processing. By eliminating the need for manual adjustments, this mechanism contributes to the overall efficiency and reliability of the machine.

2.3.4 Orientation Mechanism

- To maintain uniformity in the final output, the machine is equipped with a sophisticated orientation system. This mechanism ensures that each bill exits the machine in a perfectly aligned manner, with a consistent top-to-bottom and front-to-back configuration. Regardless of how the bills are inserted into the machine initially, they are processed and adjusted so that they emerge in an organized and standardized format.

2.3.5 Output Mechanism

- Once the bills have been fully processed, they are neatly delivered to the output tray in a uniform and well-organized stack. This feature allows for easy retrieval and handling, ensuring that the processed bills remain neatly arranged and ready for use. The output mechanism minimizes the need for manual sorting, reducing time and effort for the user.

2.3.6 Power Source

- Designed for dependable and continuous operation, this machine is powered using a standard household AC power source. Unlike battery-operated alternatives, which may suffer from inconsistencies or require frequent recharging, this AC-powered system ensures uninterrupted functionality. This reliable power source supports the machine's various automated components, allowing for seamless and efficient operation.

2.3.7 Automation Features

- To streamline the entire bill-handling process, this machine is equipped with intelligent automation features. Advanced sensors monitor and control various operations, ensuring smooth transitions between scanning, flipping, orientation, and stacking. These automated processes not only enhance user convenience but also contribute to the overall efficiency and dependability of the machine, reducing the risk of human error.

2.3.8 Efficiency

- Engineered for high-speed performance, this machine is capable of processing multiple bills in quick succession, making it an ideal solution for environments that require handling large volumes of cash. By maintaining a consistent processing rate, it maximizes productivity without compromising on accuracy. Whether used in a financial institution, retail setting, or any business that deals with cash transactions, this machine ensures rapid and reliable bill handling.

2.4 Prototype Illustration

The prototype consists of five main components: the **Entry Box**, the **Color Detector and Rejector**, the **Flipper**, the **Rotator**, and the **Output Collection Box**. Each of these components plays a critical role in ensuring that bills are processed efficiently and correctly oriented before they reach the final collection stage.

2.4.1 Entry Box

The process begins at the entry box, where a stack of bills is placed. This compartment serves as the initial loading point. Beneath the stack, a system of rollers is responsible for feeding the bills into the machine one at a time. These rollers ensure smooth and controlled movement, preventing multiple bills from entering simultaneously and reducing the risk of jams. Initially a single roller with a diamond cross pattern was used to move the bills, however, after some initial testing it was found that the roller lacked the appropriate grip and surface area to move the bills consistently and with speed. The second version of the prototype replaces the single roller with 3 gears, the space between the gears should help grip onto the bills better as well as allow faster intake into the system.

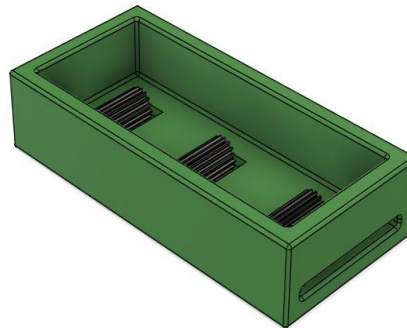


Figure 2-1: Entry Box

2.4.2 Color Detector and Rejector

As a bill moves forward from the entry box, it passes through the color detection and rejection system. This system is responsible for two key tasks:

- **Orientation Detection:** The color sensor identifies the bill's current orientation to determine whether it needs to be flipped or rotated.

- **Multiple Bill Detection & Rejection:** If the system detects more than one bill entering at once, it activates a rejection mechanism. The rollers will automatically reverse direction, sending the extra bills back to the entry box, ensuring only one bill proceeds at a time. This is done via detecting the brightness from a led situated below the bills as they pass through. The color sensor detects the brightness, and determines if there is no bills, one bill or more than one bill and determines the correct response.

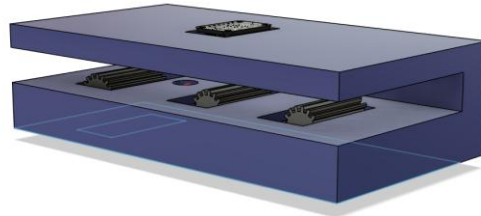


Figure 2-2: Color Detector/Bill Rejector

2.4.3 Flipper

If the color detector determines that the bill needs to be flipped, it is directed to the flipping mechanism. This component consists of a guiding pyramid that facilitates the flipping process. The bill moves upward along one side of the pyramid and then rolls back down on the opposite side, effectively flipping it to the correct orientation. If no flipping is required, the guiding pyramid lowers, providing an unobstructed path for the bill to continue forward.



Figure 2-3: Flipper Mechanism

2.4.4 Rotator

Once the bill has been properly oriented in terms of front-and-back positioning, it reaches the rotator. This mechanism determines whether the bill needs to be rotated to align correctly. If rotation is required, the bill is held securely in place at the center of the rotator while the machine rotates it to the correct position. If the bill is already properly aligned, it bypasses this stage and continues moving forward via the guiding rollers.

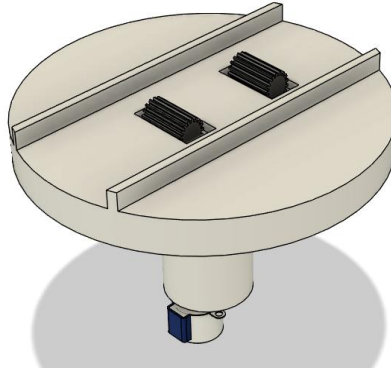


Figure 2-4: Rotating Mechanism

2.4.5 Output Collection Box

The final stage of the process is the output collection box, where the correctly oriented bills are gathered. This compartment is slightly angled for ease of access, allowing users to quickly retrieve the processed bills. A guiding structure at the end of the collection area ensures that the bills remain neatly stacked and easily graspable.

Through this structured sequence of operations, the prototype ensures that all bills are individually processed, properly oriented, and neatly collected, enhancing efficiency and ease of use.

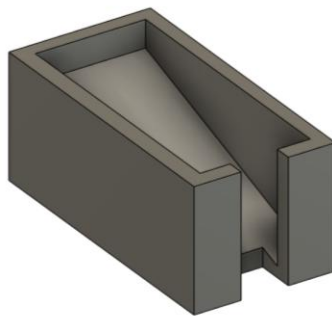


Figure 2-5: Output Collection Box

2.5 Diagrams and Flow Charts

Diagrams and flow charts serve as essential tools for visualizing the system architecture, component interactions, and operational flow. These graphical representations help in understanding the integration of various subsystems, identifying potential issues, and streamlining the development process. By illustrating both hardware and software elements, these diagrams provide a comprehensive overview of the project's design and functionality.

2.5.1 Hardware Block Diagram

The project is organized into four key areas of focus: Mechanical, Electrical, Coding, and Integration. Each section is color-coded to represent collaboration between two team members, ensuring an even distribution of responsibilities. For example, Ben and Nick will manage the electrical components, while Emily and Henry concentrate on the mechanical components. Each team member contributes to two different areas, fostering balanced teamwork and comprehensive project coverage.

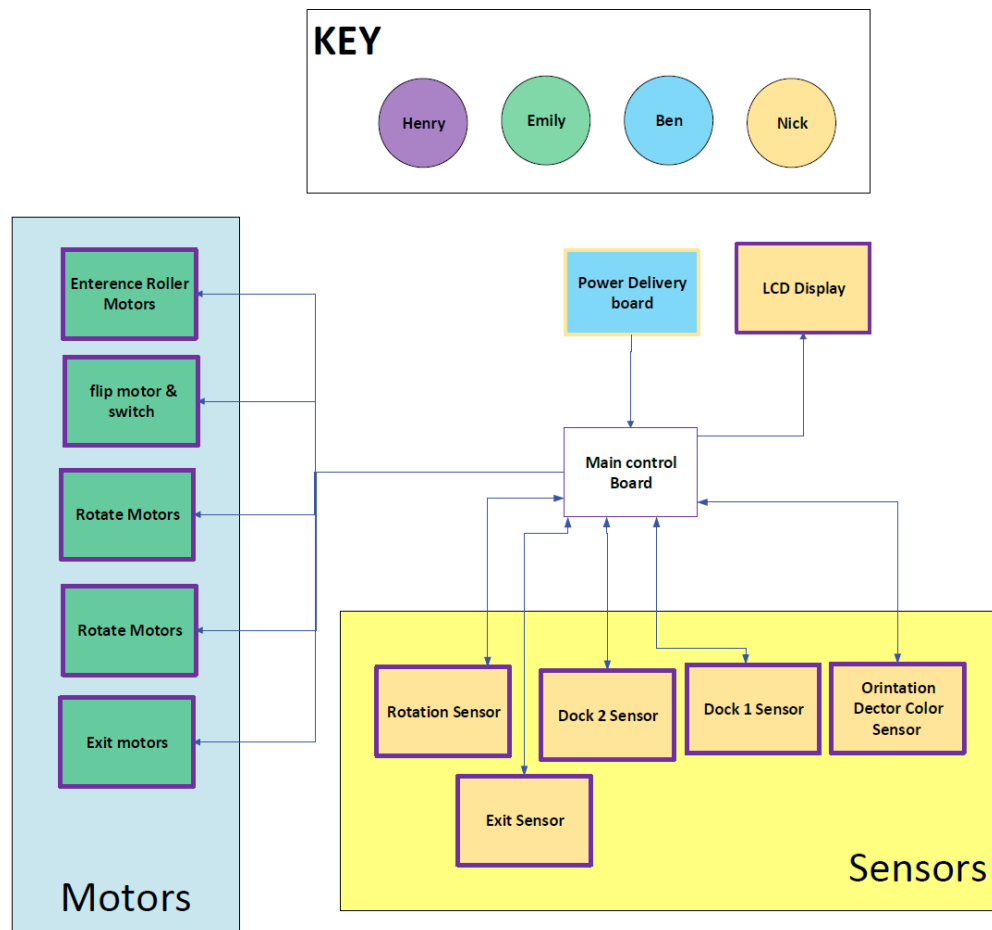


Figure 2-6: Hardware Block Diagram by Authors

2.5.2 Software Flow Chart

The flow chart found below shows the flow of the machine split into each part of sorting the bills, and highlights which parts of the machine must be utilized for each step of the sorting process. Once the machine is turned on, the entry motors are tuned on. The color sensor start detecting brightness and color. When a bill passes over the embedded LED in the color detecting stage, the sensor detects the change in brightness and compares it to the encoded ranges. If the sensor reads that the brightness is near the maximum value, then it return to spinning the gears. If the brightness is low enough that one or two bills are believed to have entered at a time, the gears are run in reverse to pull the bills back into the entry phase. If the brightness falls within he acceptable range the color sensor pulls a reading of color as the bill passes through the senior.

Each orientation has a unique color signature, for example, black then white then green then white then black white black white black would be heads up face forward of the 1 dollar bill. Reverse the sequence and you have the reverse orientation. The same applies to the back. No bill is perfectly symmetric so the technique will work for all input bills. Once the color sequence is decoded and the orientation recorded, the senior raises the lifter for the flipping phase if the bill is upside down, and lowers it if no change is necessary.

After the flipping phase, the bill moves to the rotation phase. If the bill is facing the wrong way, then the microcontroller sends a single to a stepper motor to rotate a round plate 180° then activates the last motors to move the bill to the final staging area to be picked up by the client.

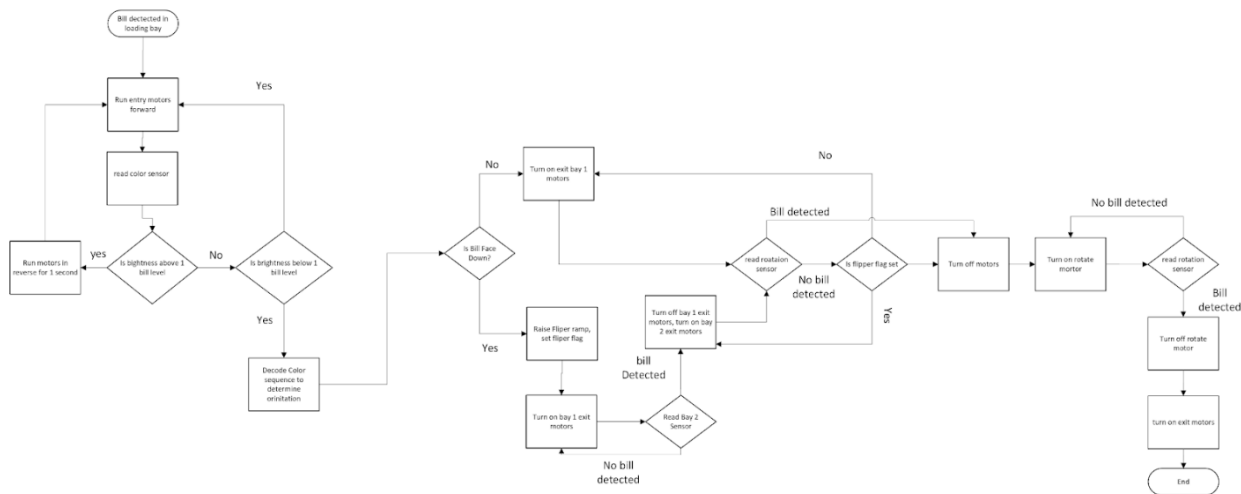


Figure 2-7: Software Flowchart by Authors

2.6 Required Specifications

Considering our design objectives and constraints, we have assessed the required engineering specifications to establish measurable criteria for the success of our project. These specifications reflect the specific engineering and design goals we consider critical for the development of our money sorting machine. For Senior Design I, we have selected the following key performance metrics to demonstrate progress toward our goals: power draw, error detection rate, bill detection accuracy, and color detection time. These metrics will serve as benchmarks to evaluate the effectiveness and reliability of our system as we move forward in the design process. The full engineering specifications are as follows:

Table 2-1 Specifications of Money Sorting Machine

Specification	Description	Target
Power Consumption	The maximum power draw of the device at full load.	Less than 60 watts.
Throughput	The minimum number of bills the device can dispense per second after the first bill reaches the output.	At least 2 bills/second.
Sorting Accuracy	The minimum average percentage of bills that are correctly sorted at the output per input stack.	At least 98%.
Error Detection Rate	The minimum rate at which the device detects multiple bills being drawn into the system simultaneously.	At least 90%
Capacity	The minimum capacity of bills that can fit into the entry box.	At least 50 bills.
Maximum Weight	The maximum weight of the finished device.	Less than 5 kilograms.
Bill Detection Accuracy	Rate at which the system's sensors accurately detects the bill at the point of input.	At least 98%.
Operating Temperature	The acceptable operating temperature range of the device during use.	0 °C - 55 °C.
Unit Manufacturing Cost	The maximum cost to manufacture a single functional unit of the device.	Less than \$100 USD.
Color Processing Time	The minimum time at which the bill's color is detected and identified.	Less than 100 milliseconds

For our senior design project, we developed this House of Quality table to systematically connect customer needs with engineering specifications. Key customer requirements include things such as portability and sorting accuracy, which are crucial for user satisfaction. These needs are linked to specific engineering requirements such as processing time and misalignment tolerance, each of

which is assigned a measurable target value. The relationship between each customer requirement and engineering characteristic is categorized as strong, weak, or none, and is displayed in the central matrix of the table. Additionally, the interdependencies among the engineering requirements themselves—such as whether improving one may positively or negatively affect another—are illustrated in the "roof" section using positive, negative, or neutral indicators. Each specification is also assigned a polarity, indicating whether an increase or decrease in the value is beneficial. This structured approach ensures that our technical design remains closely aligned with customer expectations while highlighting potential trade-offs in system performance.

QFD: House of Quality

Project: Money Saver
Revision: 2
Date: 2/3/2025

Correlation											
Positive +											
Negative -											
No Correlation											
Relationships											
Strong ●											
Weak ▽											
Polarity											
Positive +											
Negative -											
Column #		1	2	3	4	5	6	7	8	9	10
Polarity		-	-	-	+	+	+	-	+	+	-
Customer Requirements	Engineering Requirements	Power Draw	Processing Time	Size	Misalignment Tolerance	Sensor Accuracy	Quality Manufacturing Materials	Manufacturing Cost	Paper Jam Resistance	Capacity	Noise Level
+	User-Friendliness		▽		●				●	●	▽
+	Safety	●		▽			▽				
+	Portability	●		●							
+	Durability						●				
+	Sorting Accuracy				▽	●			▽		
+	Affordability							●			
Target		<20 Watts	<5 Seconds/Bill	<30x6x6 inches, 10 lbs	Up to a 15° Misalignment Tolerated	>95% Accurate	>Durability of ABS Plastic	<\$500	>95% Jams Processed	>60 Bills at a Time	<50 dB

Figure 2-8: House of Quality by Authors

Chapter 3 – Research and Investigation

This chapter explores the foundational research and investigative work conducted to inform the design and implementation of the project. A thorough understanding of existing technologies, relevant methodologies, and industry standards is essential for making informed decisions. By evaluating different approaches, materials, and techniques, the team ensures that the project is based on best practices and optimized for performance, cost, and reliability.

3.1 Technologies

A critical aspect of the project's development is the selection of appropriate technologies. This section provides an overview of the key technological choices that influence system performance, integration, and feasibility. The discussion includes hardware components, software tools, power solutions, and communication methods. Each selection is justified based on efficiency, cost-effectiveness, and alignment with project objectives.

3.1.1 Power Supply

Power management is a fundamental consideration in the design of any electronic system. This section outlines the approach taken to ensure a stable and efficient power supply for the project. The selection criteria for power sources include reliability, cost, ease of integration, and long-term sustainability. By evaluating different power supply solutions, the team identifies the most effective method for ensuring uninterrupted device operation.

3.1.1.1 Power Supply vs Device Infrastructure

Selecting an appropriate power source represents a critical design decision with far-reaching implications for device reliability, operational efficiency, and long-term maintenance. Our comprehensive evaluation examined multiple power delivery methodologies, conducting an extensive comparative analysis between battery-powered and grid-connected solutions.

Battery power initially presented attractive characteristics, including portability, minimal infrastructure requirements, and standalone operational potential. The technology offers perceived flexibility and reduced electrical infrastructure dependency, making it an appealing initial consideration for device power management.

Nevertheless, battery power presents significant systemic limitations that ultimately rendered it unsuitable. These constraints include inconsistent power delivery, periodic replacement requirements, higher cumulative operational costs, environmental waste from battery disposal, performance degradation over time, and inherent sensitivity to temperature and environmental conditions.

In contrast, grid-connected power infrastructure provides substantial advantages. Direct electrical connectivity ensures consistent, uninterrupted power supply, eliminates battery replacement cycles, reduces long-term maintenance overhead, and supports continuous, predictable device performance. This approach minimizes environmental waste associated with battery consumption and enables seamless plug-and-play device integration.

The device's intended deployment—a fixed-location installation with minimal positional variance—strongly favors direct electrical grid connectivity. By utilizing a standard AC to DC-power adapter, we establish a robust, low-maintenance power delivery mechanism. This approach prioritizes operational reliability, reduces the total cost of ownership, and aligns with sustainable engineering principles.

Our strategic power design rationale emerges from a nuanced assessment of technical performance, economic efficiency, and environmental responsibility. Direct grid power represents the most pragmatic solution, offering a superior long-term value proposition compared to battery-dependent alternatives.

The chosen power infrastructure strategy reflects a deliberate engineering decision that balances multiple critical considerations. Consistent power delivery, minimal maintenance requirements, cost-effectiveness, environmental sustainability, and predictable performance characteristics collectively informed our comprehensive approach to power management.

In conclusion, grid-connected power supply offers the most compelling technical and economic advantages for our device's operational ecosystem. This sophisticated approach to power management demonstrates a forward-thinking design philosophy that prioritizes reliability, efficiency, and sustainable technological development.

3.1.1.2 Power Distribution

To enhance the reliability, availability, simplicity, and efficiency of our project, we opted to use AC mains power as the primary power source. However, as the project's electronic components—such as sensors, microcontrollers, and motors—operate on low DC voltages, converting AC power to a suitable DC voltage is a critical step in ensuring effective power delivery.

The process of converting AC mains power to low DC voltage involves several key stages. First, a transformer is used to step down the 120V AC from the mains to 12V AC, efficiently reducing the voltage without significant power loss. Following this, a rectifier is employed to convert the AC waveform into DC. To ensure a smooth and stable output, a voltage regulator is incorporated to eliminate ripples and fluctuations. By implementing these stages, the system is able to deliver a consistent 12V DC output, meeting the requirements of the electronic components and ensuring reliable operation.

We evaluated two potential solutions for achieving the conversion from AC mains power to low DC voltage:

- 1. Transformer-Based Circuit:**

This solution involves designing a custom circuit that includes a power cord, transformer, rectifier, voltage regulator, and power distribution block. The transformer windings would be manually constructed, while the rectifier and voltage regulator circuit would be custom-designed to provide a stable and reliable DC output.

- 2. AC Power Supply Adapter:**

This approach utilizes a commercially available power supply adapter in conjunction with a power distribution block. The adapter consolidates the power cord, transformer, rectifier,

and voltage regulator into a single unit, offering a simplified implementation while ensuring a consistent and reliable DC output.

Figure 3.1 outlines the components of a standard AC power supply adapter, highlighting their placement within the circuit and their impact on the voltage waveform.

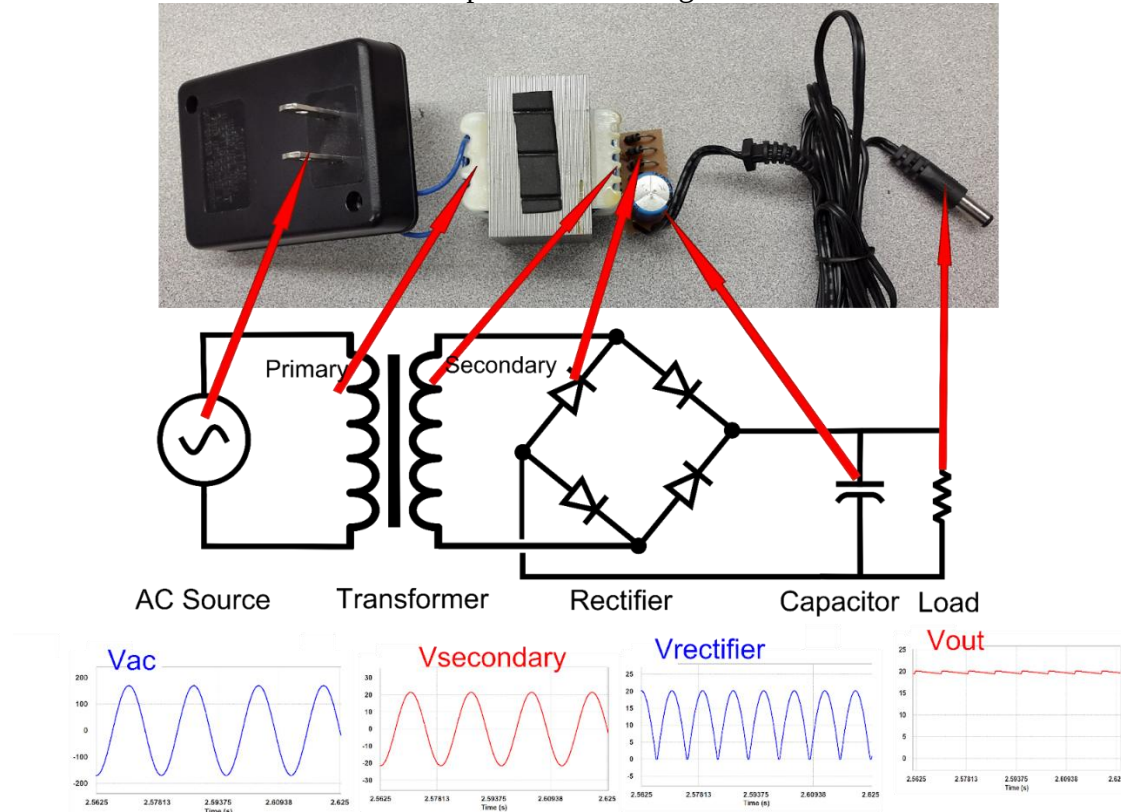


Figure 3-1: Diagram Analysis of AC Power Supply

The characteristics used to compare the two solutions were selected based on their relevance to the project's needs. These characteristics include:

- **Safety:** Ensuring a safe power implementation is crucial to minimize the risk of injury and equipment damage.
- **Reliability:** A reliable power solution is essential for smooth operation, reducing the need for frequent maintenance.
- **Flexibility:** Flexibility is important due to the evolving nature of the project's architecture.
- **Design Simplicity:** A straightforward design is preferred to facilitate efficient power transfer and minimize potential failure points.
- **Form Factor:** Given the project's limited interior space and the goal of maintaining a compact design, a small and efficient power solution is necessary.

The critical characteristics of each solution are compared below to identify the most suitable power solution for the project.

Table 3-1 *Summary of Transformer vs AC Power Supply Adapter Analysis*

	Transformer Circuit	AC Power Supply Adapter
Safety	Transformer circuits are less safe due to multiple potential failure points. Additionally, manual implementation of fuses, overload protection, and insulation are required, increasing the risk.	AC power supply adapters are safer because they come with pre-integrated safety features, eliminating the need for additional implementation.
Reliability	Transformer circuits are less reliable since the failure of individual components can affect overall functionality. Furthermore, the output voltage tends to be less stable compared to an AC power supply adapter.	AC power supply adapters are more reliable as they are sealed, maintenance-free, and offer stable voltage output. They typically achieve over 90% efficiency.
Flexibility	Transformer circuits are more flexible since individual components can be modified or replaced as needed, allowing for customization.	AC power supply adapters are less flexible because the components inside are sealed, preventing interaction or modification.
Design Simplicity	Transformer circuits are more complex, requiring multiple components and advanced knowledge to design and assemble all the necessary parts.	AC power supply adapters are simpler, offering a preassembled solution with all necessary components integrated into a single unit.
Form Factor	Transformer circuits, despite having small individual components, require a large amount of space to integrate them, which can lead to wasted space.	AC power supply adapters are more compact, with all components consolidated into a single enclosure.

3.1.1.3 XWNV AC Adapter Power Supply – ANU-090100A

The DC 12V 5A Power Supply Adapter Converter is designed to provide reliable and stable power for a variety of low-voltage applications. With an input range of 100-240V AC, it is compatible with most global power systems, making it versatile for international use. The adapter outputs a consistent 12V DC at 5A, ideal for powering devices such as LED strips, including popular models like the 5050 and 3528 LED strip modules. Equipped with a 5.5x2.5mm DC output jack, it ensures a secure and efficient connection for powering lights or other low-voltage electronics. This power supply is a compact and reliable solution for projects requiring consistent 12V DC power, with built-in protection to safeguard against overloading and short-circuiting.

3.1.1.4 HIT AC Adapter Power Supply – LX60-120500-D1

The "Hit Lights 12V 5A Power Supply Adapter" is a UL-listed transformer designed to convert 120VAC to a stable 12VDC output, making it an ideal power source for LED strip lights and other low-voltage devices. With a 12V output at 5 amps, this power supply is capable of delivering up to 60 watts of power, ensuring reliable performance for a variety of applications. Manufactured by HIT International Consulting, LLC, the adapter provides a secure and consistent power supply with built-in safety features, such as overload and short-circuit protection. Its compact design and reliable functionality make it a suitable choice for projects requiring efficient, low-voltage power delivery.

3.1.1.5 Insignia AC Adapter Power Supply – NS-AC1200

The "Insignia™ 15.6W 4.9 ft Universal AC Adapter" is a versatile power supply designed to provide reliable and consistent power for various electronic devices. With an output of 15.6 watts, this adapter is suitable for powering small devices that require a low-voltage AC input. The 4.9-foot cord length offers flexibility in placement and use, making it ideal for a range of applications. Manufactured by Insignia, the adapter is compact, lightweight, and easy to use, providing a straightforward solution for powering devices in home or office settings.

3.1.1.6 Power Supply Comparison

The three power supplies evaluated—XWNV ANU-090100A, HIT LX60-120500-D1, and Insignia NS-AC1200—each offer distinct advantages. The XWNV adapter provides reliable 12V 5A power with international compatibility, making it suitable for various low-voltage applications. The HIT adapter is UL-listed and ensures safety with built-in protection features, offering stable performance. The Insignia adapter, while lower in power output at 15.6W, is versatile for smaller electronic devices. Based on stability, efficiency, and application needs, the XWNV and HIT adapters are preferable for powering high-current devices, whereas the Insignia adapter is better suited for low-power applications.

Table 3-2 Summary of AC Adapter Power Supply Comparison by Authors

	ANU-090100A	LX60-120500-D1	NS-AC1200
Cost	\$9.11	\$19.99	\$19.99
Form Factor (cm)	3 x 4 x 7.5	3.1 x 5.1 x 11.7	6.3 x 4.21 x 2.52
Power	60W	60W	15.6W
Output Voltage	12V	12V	12V
Output Current	5A	5A	1.3A
Connector Type	Barrel Jack	Barrel Jack	USB/Barrel Jack

3.1.2 Power Distribution Block

In any electrical system, power distribution plays a crucial role in ensuring stable and efficient operation. A power distribution block (PDB) serves as a centralized hub for distributing electrical power from a primary source to multiple components while preventing excessive load on a single connection. The selection of a suitable PDB is essential for maintaining electrical integrity, minimizing resistance losses, and preventing system failures.

A well-designed PDB enhances cable management by reducing wiring complexity, improving safety, and allowing for future expandability. This section explores different power distribution blocks that were considered for the project, highlighting their strengths and trade-offs based on key selection criteria.

3.1.2.1 Optimal Performance and Power Distribution

The next step is to choose a suitable power distribution block (PDB) to efficiently distribute power throughout the project without overloading any single connection. The PDB plays a crucial role in ensuring the reliable and safe delivery of power to all components, preventing overloading or underpowering that could lead to system instability or failure. A properly selected PDB consolidates multiple power connections into a single unit, reducing clutter and improving the overall organization of the system. To identify the best PDB, four key characteristics were considered:

- **Cost:** Given the project's limited budget, a cost-effective PDB is preferred.
- **Electrical Ratings:** The PDB's electrical ratings must be compatible with the project's power requirements. If the PDB cannot handle the required load, it may overheat or fail, compromising performance and safety.
- **Port Count:** A higher number of output ports allows for greater flexibility in powering multiple components without the need for additional distribution methods, simplifying the overall design.
- **Size:** The PDB must be compact enough for seamless integration into the project without occupying excessive space. A well-sized PDB ensures efficient use of available space, maintaining a clean, organized, and functional setup.

By carefully considering these factors, the right PDB will contribute to the project's long-term success, ensuring stable operation and minimizing the risk of electrical issues.

3.1.2.2 Cabur – QBLOK7001

The "ASI QBLOK7001 Neutral Power Distribution Block" is a high-quality power distribution solution designed for efficient and reliable power management. Manufactured by Cabur, this model is built for use with DIN rails, offering a compact and organized method for distributing power across multiple connections. The block supports wire sizes up to 8 AWG, ensuring compatibility with a range of electrical setups. With seven connection points, the QBLOK7001 provides flexibility for distributing neutral power to various components, making it ideal for industrial or commercial applications. The blue-colored block comes in a pack of 10, offering both convenience and cost-effectiveness for large-scale projects.

3.1.2.3 Mofeez – 98MF18043

The "MOFEEZ Power Distribution Block Bus Bar" is a robust and reliable solution for managing high-power electrical connections. Manufactured by Mofeez, this model features four 5/16" posts and six #8 screw terminals, offering flexibility and durability for various electrical setups. With a maximum rating of 48V and 250A, it is ideal for high-current applications, providing secure and efficient power distribution. The block comes in a pair, with red and black colors, making it easy to distinguish between positive and negative connections. This power distribution block is perfect for automotive, industrial, and other heavy-duty applications requiring reliable power handling.

3.1.2.4 Square D – 9080LBA361101

The "SQUARE D Miniature Distribution Block" is a compact and efficient solution for distributing electrical power in various industrial and commercial applications. Manufactured by Square D, this distribution block features three poles and is designed for surface mounting, offering a space-saving and secure installation. The block is ideal for managing power distribution in systems that require compact and reliable components. With its durable construction, the SQUARE D distribution block ensures long-lasting performance and safe power handling.

3.1.2.5 Power Distribution Block Comparison

The selection of the most appropriate power distribution block required an evaluation of various models based on performance, cost, durability, and ease of integration. Table 3.3 provides a comparative analysis of the three shortlisted PDBs, summarizing their key specifications and suitability for the project.

Table 3-3 Summary of PDB Comparison by Authors

	QBLOK7001	98MF18043	9080LBA361101
Cost	\$19.47 for 10	\$26.00 for 2	\$24.94
Output Current (Maximum)	63A	250A	115A
Output Voltage (Maximum)	500V	48V	600V
Port Count	7	4	3
Size (cm)	1.60 x 5.30 x 4.00	17.02 x 3.30 x 5.33	4.11 X 5.82 X 5.38

3.1.3 Motors

Motors are an essential component of many systems, enabling mechanical movement through the conversion of electrical energy into kinetic energy. The choice of motor depends on factors such as the power requirements, precision needed, environmental conditions, and size constraints. Various motor types, including brushed and brushless DC motors, as well as AC motors, offer distinct benefits and limitations. For small-scale, precise, and low-power applications, DC motors are often the most suitable choice due to their ease of control and compact form.

3.1.3.1 AC vs DC Motors

Motors consist of two main components: the armature and the stator. The stator is the stationary part of the motor and contains a coil of copper wire. When DC power is supplied to the wire, it generates a magnetic field. This magnetic field interacts with the permanent magnets in the armature, causing it to rotate and align with the field. To ensure continuous rotation, a commutator—an electrical switch—reverses the direction of current every half revolution, preventing the armature from aligning with the magnetic field.

Motors are classified into DC and AC types. AC motors are typically more efficient at producing consistent power over time, making them ideal for high-power applications. In contrast, DC motors are well-suited for precision control and low-power operations. Since our system operates on DC and requires minimal power with high precision, our focus will be exclusively on DC motors, and AC motors will not be considered for this application.

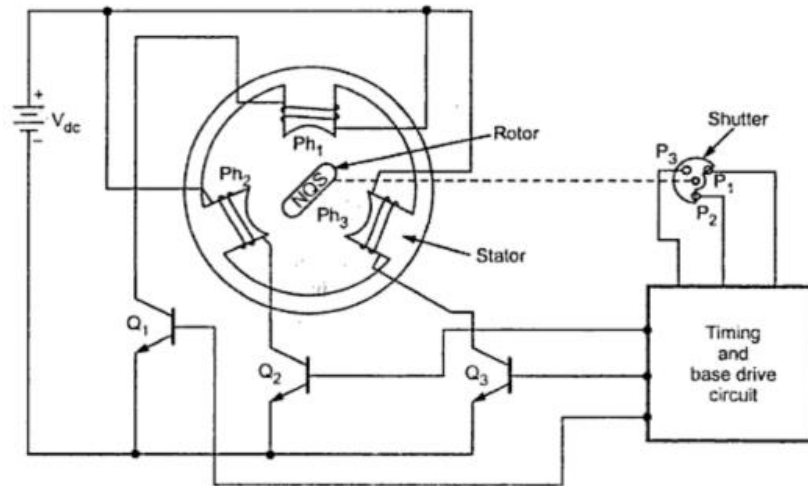


Figure 3-2: Brushless DC Motor Diagram

3.1.3.2 G12-N20 Geared Mini DC Motor

The G12-N20 Geared Mini DC Motor is a light weight high torque and low RPM motor produced and sold by Handson Technology. The small size and power requirements makes the motor perfect for use in robots or small precise movement applications. The motor is primarily constructed out of metal which gives the build a sturdy frame that is resistant to vibrations. The motor can operate with voltages ranging from 6-12V, and normally consumes 70 mA but can pull as much as 1 A when stalled. At full load the motor consumes 12W of electricity, at minimum it can operate with as low as 42 mW. The Motor has variable RPM based on the voltage provided, at 3V the motor reaches 50 RPM, at 6V the motor spins at 100 RPM and reaches a max speed of 200 RPM when 12 V is applied. Depending on the voltage provided, the motor can provide anywhere from 2-16kg*cm of torque. The entire motor only takes up a 36 x 12 x 10mm, with the gear shaft itself measuring 3 by 10 mm. Due to its small size the total motor weighs only 10g. Additionally, the motor is designed to operate within 0-70 degrees celsius. Lastly the motor can be bought from a variety of different online suppliers and distributors for as low as \$1.68 from aliexpress and as high as \$15.00 from Digit Key.

3.1.3.3 M260

The M260 mini motor from SparkFun electronics is a small hobby dc motor with a 6mm gear attached to the gear shaft. The M260 is the lowest power motor under consideration will a operating voltage ranging from 1-3 V, and a current consumption of 110 mA under load and 800 mA when stalled. Thus the M260 can consume anywhere from .11- .33 W, significantly lower than any other motor under consideration. Despite its lower power draw, the M260 has a rated speed of 6600 plus or minus 10% RPM. Following its low power draw, the M260 is the smallest of the motors under consideration with a footprint of only 11.9 x 15.3 mm but is the heaviest with a weight of 26g. Furthermore, the M260 is rated to be operational between -5 and 40 degree celsius. The M260 is readily available from numerous online retailers and distributors with a price that hovers around \$2.10 at the time of writing.

3.1.3.4 Adafruit DC Toy / Hobby Motor - 130 Size

The Adafruit DC Toy / Hobby Motor -130 Size (M130) is produced by the aforementioned electronics manufacturer Adafruit. The motor operates within 4.5 to 9 V, placing it in the middle of the two previously compared motors. The M130 pulls 70mA under load and pulls 500mA when stalled. Thus the M130 consumers 310 mW at minimum, and can pull as much as 4.5W under full load while stalled. The M130 exceeds the other two motors under consideration with a speed of 9100 ± 1800 RPM making it the fastest motor under consideration. However the increase speed comes at a reduced torque with the M130 only rated to produce 20 g*cm on start up and 10 g*cm consistently.

The M130 has a foot print of 27.5mm x 20mm x 15mm, with a shaft length of 8mm x 2mm. This places it larger than the M260 but smaller than the G12-N20 Geared Mini DC Motor. The M130 weighs 17.5g once again placing it squarely in the middle of the motors under consideration. As Adafruit is an American based company, the M130 can easily be sourced from Adafruit's online site, or through other standard distributors such as Digikey for around \$2.00 at the time of writing.

3.1.3.5 Motor Comparison

The comparison of the motors considered for this application shows varying trade-offs in terms of size, power consumption, torque, speed, and operational voltage. The table below summarizes key parameters such as voltage range, current consumption, power draw, speed, torque, and other essential specifications. This comparison will help guide the selection of the most appropriate motor for the project's specific requirements, such as efficiency, size constraints, and desired performance characteristics.

Table 3-4 Summary of Motor Comparison by Authors

	G12-N20 Geared Mini DC Motor	M260	Adafruit DC Toy / Hobby Motor - 130 Size
Voltage (V)	3 - 12 V	1-3	4.5-9
Current	70 mA - 1 A	110 mA - : 800 mA	70 mA -500 mA
Power Consumption	42 mW - 12 W	0.11 - 0.33 W	0.42 W
Speed (RPM)	50 - 200 RPM	$6600 \pm 10\%$	9100 ± 1800 rpm
Torque (Nm)	2 - 16 kg*cm	N/A	20 g*cm
Size	36 x 12 x 10mm	11.9 x 15.3 mm	27.5mm x 20mm x 15mm
Weight	10g	26g	17.5g
Shaft size	3 x 10mm	6 mm and 10 teeth gear	8mm x 2mm diameter
Cost	\$1.68-\$15.00	\$2.10	\$2.00
Temp Range	0-70°C	-5°C- 40°C	-

3.1.4 Stepper Motors

For the rotating plate mechanism in our money-sorting device, a stepper motor was chosen for its precise positional control, which is essential to prevent jams and ensure accurate bill handling.

Unlike brushed or brushless DC motors that focus on speed, stepper motors move in defined increments, allowing for controlled, reliable rotation.

The stepper motor's holding torque is another key advantage, keeping the plate stationary when needed without extra braking components. Its ability to operate without feedback systems simplifies the design and lowers costs. Overall, its precision, reliability, and simplicity make it the most suitable choice for the rotating plate mechanism, compared to the other motors used in our project.

3.1.4.1 StepperOnline - 17HS08-1004S

The 17HS08-1004S from StepperOnline is a NEMA 17 bipolar stepper motor with a 1.8-degree step angle, offering precise positional control. It features a holding torque of 16 N-cm (22.6 oz-in), and operates at a rated current of 1.0 A per phase with a rated voltage of 3.7 V. This results in a power consumption of approximately 3.7 W per phase under normal operating conditions. With a body size of 42 x 42 mm and a length of 20 mm, the 17HS08-1004S is one of the more compact NEMA 17 motors available. It has a 5 mm shaft diameter and weighs approximately 140 g. The motor is rated to operate in ambient temperatures ranging from -20 to 50°C.

3.1.4.2 StepperOnline - 17HS13-0404S1

The 17HS13-0404S1 from StepperOnline is a NEMA 17 bipolar stepper motor with a 1.8-degree step angle, providing precise rotational control. It delivers a holding torque of 26 N-cm (36.8 oz-in) and operates at a rated current of 0.4 A per phase with a driving voltage of 12 V, resulting in a power draw of approximately 4.8 W per phase. The motor's compact dimensions are 42 x 42 mm with a body length of 34 mm, and it features a 5 mm diameter shaft extending 20 mm. Weighing approximately 230 g, it is suitable for applications requiring moderate torque with low current consumption.

3.1.4.3 Adafruit - XY42STH34-0354A

The XY42STH34-0354A from Adafruit is a NEMA 17 bipolar stepper motor with a 1.8-degree step angle, providing 200 steps per revolution for precise motion control. It operates at a rated voltage of 12 V and a current of 350 mA per phase, resulting in a power draw of approximately 4.2 W per phase. The motor delivers a holding torque of 15.7 N-cm (22.2 oz-in), making it suitable for applications requiring moderate torque. The motor features a 42 x 42 mm body with a length of 34 mm and a 5 mm diameter shaft extending 24 mm, including a machined flat for secure coupling. It weighs approximately 220 g and includes 8-inch, 4-wire leads with color-coded pairs for straightforward integration with standard stepper drivers.

3.1.4.4 Stepper Motor Comparison

To determine the most suitable stepper motor for the rotating plate mechanism in our money-sorting device, we compared three NEMA 17 bipolar stepper motors: StepperOnline 17HS08-1004S, StepperOnline 17HS13-0404S1, and Adafruit XY42STH34-0354A. The comparison is based on key performance metrics, including holding torque, power consumption, physical dimensions, and current requirements.

Table 3-5 Summary of Stepper Motor Comparison by Authors

	StepperOnline 17HS08-1004S	StepperOnline 17HS13-0404S1	Adafruit XY42STH34-0354A
Voltage (V)	3.7	12	12
Current/Phase (mA)	1000	400	350
Power Consumption/Phase (W)	3.7	4.8	4.2 W
Torque (N-cm)	16	26	15.7
Step Angle (Degrees)	1.8	1.8	1.8
Size (mm)	42 x 42 x 20	42 x 42 x 34	42 x 42 x 34
Weight (g)	140	230	220
Cost (USD)	\$7.99	\$12.50	\$14.00

3.1.5 Motor Control Unit

A Motor Control Unit (MCU) is essential for managing and controlling the operation of motors in a system. It ensures that the motor receives the right amount of voltage, current, and power for efficient performance, while also regulating parameters such as speed, torque, and direction. Additionally, the MCU helps protect the motor from issues like overheating and excessive current draw, thereby increasing the lifespan and reliability of the system. MCUs can control a wide range of motor types, including both brushed and brushless DC motors, stepper motors, and even AC motors. Depending on the complexity of the system, an MCU may incorporate various control techniques, such as Pulse Width Modulation (PWM), H-Bridge circuits, and feedback mechanisms, to provide precise control over motor behavior.

3.1.5.1 MCU Analysis

Motors are a complex and important part of any system. They require a lot of power compared to other components in a system, often requiring full Watts to operate at max speed. The role of a Motor Control Unit (MCU) is to monitor and regulate temperature, current, and voltage, and control the speed, torque, direction, and corresponding power output of a motor. For AC motors the MCU is also responsible for converting standard direct current (DC) into the correct phase of alternating current (AC) for the output motor.

The MCU can control current and voltage through a series of regulators to ensure that the motor only receives the amount of voltage and current it requires. This allows multiple different types of motors with different specifications can be connected to one MCU, improving efficiency and lowering cost. Furthermore MCU's can monitor temperature through a temperature indicator circuit which through a series of transistors and diodes and a ADC can convert the temperature of the surrounding silicon into a voltage. That voltage can then be normalized and then used to control a temperature cut off switch or other components.

The MCU can control the speed and torque through the use of pulse wave modulation (PWM). The MCU controls the voltage and current to the motor, or through $P = W \cdot A$, the power to the motor. Power can also be represented by speed times torque, $P = \omega \cdot \tau$. Thus by controlling the current going to the motor, the MCU can adjust the speed and torque of the motor as needed for any specific application. For direction the MCU architecture uses two half bridges (H-bridges). As

motors spin using induction, reversing the polarity of the circuit reverses the direction of the motor. An H-bridge uses a combination of four switches, usually transistors, to control which side of the motor receives positive current and which is connected to ground.

The H-bridges can be constructed using switches, MOSFETs, or BJT transistors. Switches are large and are most costly than transistors and thus are impractical for most applications outside of prototyping. Modern MCUs contain an integrated circuit (IC) that contains an array of H-bridges that can be directly accessed through I/O pins along with a couple control pins to control the direction of the H-bridges. These ICs are designed using either MOSFETs or BJTs due to their small size and cost. MOSFETs are generally preferred over BJTs due to their lower voltage drop, on state resistance and leak current. However, BJTs are more resilient to power fluctuations and other environmental conditions, thus are more suited to extreme conditions and can generally be produced for lower cost. For this system, both are sufficient enough thus MCUs will be considered without discretion.

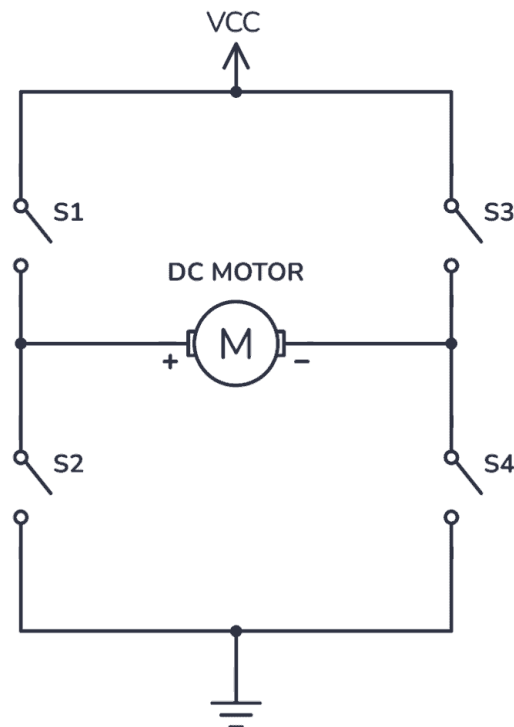


Figure 3-3: Half Bridge Example

3.1.5.2 L298P

The L298P is a robust and reliable motor control unit manufactured by STMicroelectronics, a leading electronics provider. In use since the 1980s, the L298P has established itself as a dependable, high-performance integrated monolithic circuit. It is a high-voltage, high-current dual full-bridge driver capable of bi-directionally controlling up to two DC motors or one stepper motor. Additionally, the L298P includes two sensor pins for more precise motor control.

The L298P requires a 5V input to power its logic circuitry while delivering up to 50V to the connected motors. It can output up to 2 amps continuously for DC motors, with a peak output of 3A for short durations (less than 100ms), or 2.5A with 80% duty cycle. At full load, the L298P can dissipate a maximum of 25W of power. The device operates using BJT transistors, ensuring efficient power management.

The L298P features 20 I/O pins, including two unused pins, four ground pins, two input pins for each motor circuit (A and B), two enable pins, and two sensor pins. Each motor circuit can be disabled via an active high enable line, and the direction of motor rotation can be controlled using two input pins. For example, setting input 1 (IN1) to high and input 2 (IN2) to low drives the motor forward, while setting IN1 to low and IN2 to high drives the motor in reverse. When both inputs are set to the same value, the motor stops. The sensor pins are internally connected to the motor lines, and variable resistors can be used to provide fine control over the motor speed. If an unacceptable sensor value is reached, an interrupt can be triggered to disable the motor.

The L298P can be easily controlled through its input pins using binary logic, and an open-source library for Arduino simplifies the control process. Motor speed can be adjusted via one of the PWM pins on the microcontroller. The microcontroller, measuring just 6mm x 5mm x 3.2mm, is compact enough to fit within our size constraints, allowing for parallel use to control multiple motors as needed. The L298P is available for \$12.00 as a standalone chip from distributors like DigiKey or as a breakout board for just \$1.00 from platforms such as Amazon and AliExpress.

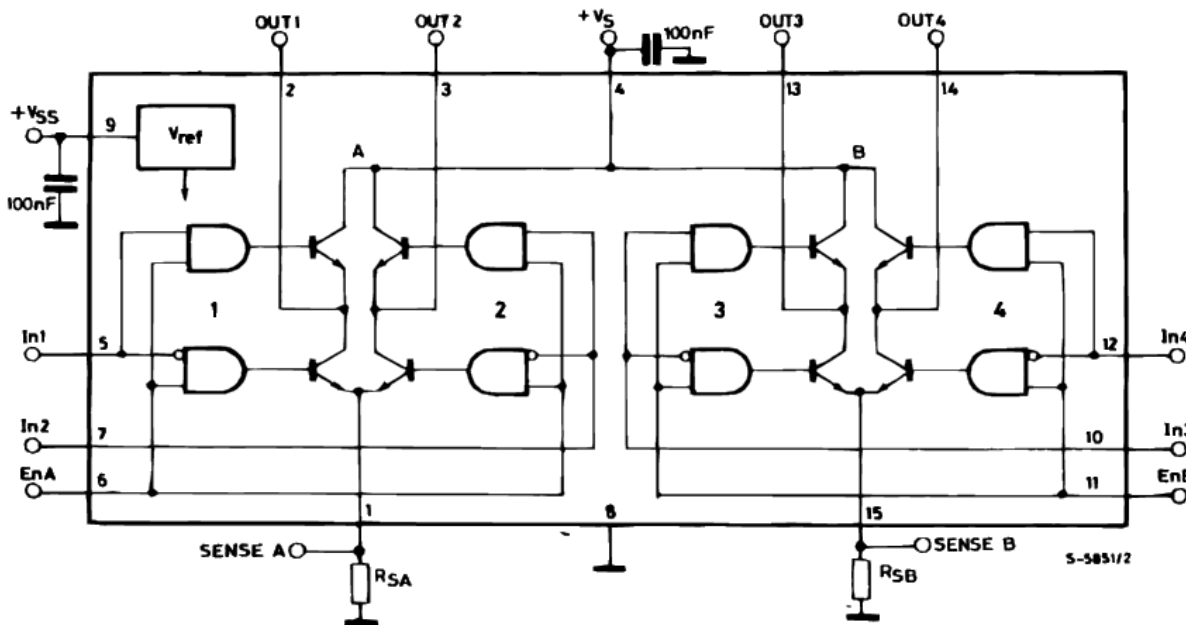


Figure 3-4: Schematic for L298

3.1.5.3 L9110S

The L9110S is a compact two-channel push-pull power amplifier motor control chip manufactured by UMW, a prominent semiconductor company. It is the smallest chip under consideration in this design, featuring a single half-bridge, which means it can support only one bi-directional motor per chip.

The L9110S operates with an input voltage range of 2.5V to 12V and includes internal power regulation to ensure that the logic receives the proper voltage while passing the input voltage to the motor. It can handle a maximum current output of 800mA and dissipates a maximum of 9.6W when running at 12V.

With just 8 I/O pins, the L9110S includes two ground pins, two VCC pins, one output line for each motor (A and B), and two control pins. The motor's direction can be controlled by applying a PWM signal to the input pins—sending a signal to the A pin drives the motor forward, while a signal to the B pin drives it backward. However, the L9110S lacks sensor pins and built-in overvoltage or current protection, so additional circuitry would be needed for protection.

Similar to the L298P, the L9110S is controlled via digital inputs to the control lines. An open-source library for the Arduino IDE simplifies the programming process. The L9110S has the smallest physical footprint of the chips considered, measuring only 6mm x 5mm x 3.2mm, which not only allows it to fit within tight size constraints but also makes it easier to use multiple chips in parallel to drive the motor array in our final design.

3.1.5.4 DRV89XX-Q1

The DRV89XX-Q1 family of chips, developed and manufactured by Texas Instruments (TI), is a series of integrated multi-channel half-bridge drivers designed specifically for automotive applications. This family includes models with 4, 6, 8, 10, or 12 half-bridges and is capable of driving both brush-DC motors and stepper motors in independent, sequential, or parallel modes. These chips can control motor direction (forward or backward), coast the motor, or fully brake the motor. The DRV89XX-Q1 stands out due to its extensive functionality, offering a range of integrated components and systems not available in other motor control units.

The DRV89XX-Q1 family supports an input voltage of 3.3V or 5V for logic, with a pass-through voltage range of 4.5V to 32V for the motors. It can output a maximum current of 6A across all lines, with each individual line supporting up to 1A, dissipating up to 280W. Additionally, the family features a low-power sleep mode, consuming only 1.5 μ A of current when the motors are idle.

A key feature of the DRV89XX-Q1 family is its built-in components, including SPI programmable PWM generators. The lower-end models have four generators, while the higher-end models have eight, freeing up ports on the microcontroller for other components. These PWM generators offer an 8-bit duty cycle resolution, making the system more efficient. Furthermore, the family includes comprehensive protection features such as over and under voltage lockout, overcurrent protection, and Enhanced Open Load Detection, preventing errors when there is an open circuit in the load line. The family also integrates a thermal warning and shutdown circuit that can be programmed to disable the chip when a predefined temperature threshold is reached.

The DRV89XX-Q1 family utilizes PWM to control motor speed, but unlike other motor control chips, it has the added functionality of using the built-in PWM generators. These generators can produce signals with frequencies ranging from 80 Hz to 2000 Hz. The chip requires 5 MHz, 16-bit SPI communication for control, a more complex communication protocol than simpler MCUs.

Fortunately, an open-source Arduino library is available to simplify programming and communication with the DRV89XX-Q1 family.

The DRV89XX-Q1 family can be purchased directly from TI or through distributors like Digikey. Prices range from \$1.05 for the DRV8904-Q1 to \$1.56 for the DRV8912-Q1 when purchased through TI, or from \$2.78 to \$5.33 when bought from Digikey.

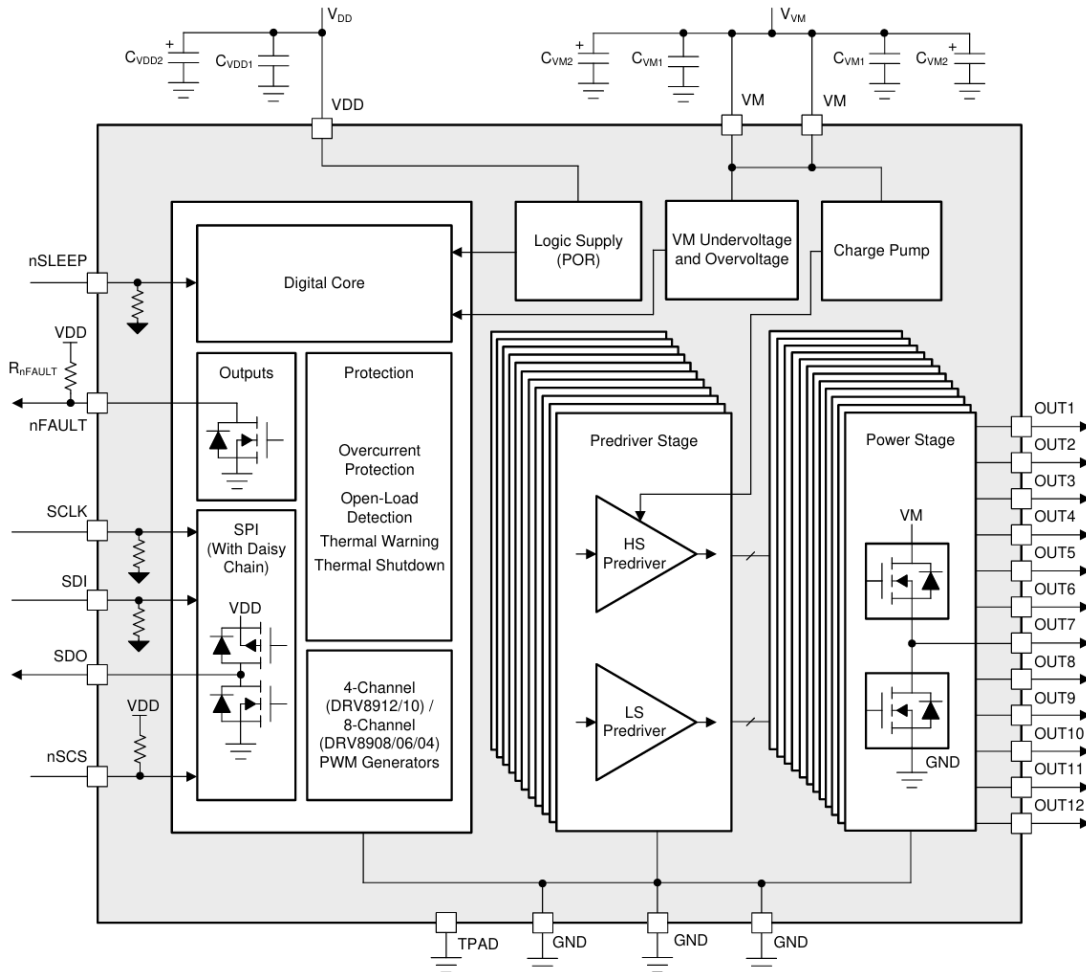


Figure 3-5: Block Diagram of the DRV89XX-Q1

3.1.5.5 MCU Comparison

The comparison of various Motor Control Units (MCUs) helps identify the most suitable option for the system based on factors such as voltage range, current handling capacity, physical size, power dissipation, and control features. By evaluating the capabilities of different MCUs, including the number of I/O pins, the availability of integrated H-bridges, and the ease of programming (such as compatibility with microcontroller platforms like Arduino), a more informed decision can be made regarding which MCU best meets the system's requirements. The table below summarizes key specifications and features of each MCU, providing a side-by-side comparison to aid in the selection process.

Table 3-6 Summary of MCU Comparison by Authors

	DRV89XX-Q1	L9110S	L298P
Number of Half Bridge	4,6,8,10, and 12	1	2
Input Voltage (chip) (V)	0-5.5V (norm 3.3-V and 5-V)	2.5-12 6 (TYP)	4.5 - 7 5 (TYP)
Output Voltage (V)	4.5 - 32V (requires input of same value)	0-V _{cc}	4.8 - 50
Output Current (A)	6	.800	3 (non constant) 2 (constant)
Power Rating (W)	27-280	2-9.6	25
Supported Motor Types	brushed-DC (BDC) motors or stepper motors	Steeper & DC	brushed-DC (BDC) motors or stepper motors
MISC Protection	nFAULT pin output Enhanced open load detection (OLD) Thermal warning and shutdown (OTW/OTSD)	No	Over temp protection
Control Method	PWM	PWM	PWM
Communication Protocol	SPI	Binary	binary
Libraries	Arduino (open source)	Arduino (open source)	Arduino
Speed Range	80-2000HZ (PWM)	N/A	N/A
Over Voltage/Current Protection	Yes	No	Yes through sense pins
Dimensions	7.80 mm × 4.40 mm	6mm x 5mm x 3.2mm	16 x 11.1 mm
Temperature Range (°C)	-40 to 125	-30-85	-25 to 130
Cost	\$1.05-1.56 (TI) \$2.78-5.33 (digit key)	\$0.98	\$1-12.00

3.1.6 Sensors

In any system design, especially one involving motor control and automation, sensors play a critical role in monitoring the environment and providing feedback to the system. This feedback is essential for adjusting parameters such as speed, position, and safety conditions. Sensors can detect a wide range of physical phenomena including motion, proximity, temperature, and magnetic fields, and the choice of sensor depends on the specific needs of the application.

In this project, three types of sensors are particularly relevant: IR break beam sensors, through-beam optical sensors, and magnetic sensors. These sensors each have their unique strengths and applications, offering different levels of sensitivity, response times, and power consumption.

3.1.6.1 Sensor Reliability

When designing a system with as many interconnecting parts as we have, it is important to monitor and adapt to any changes in the expected outcome as fast as possible, this requires extensive sensing devices embedded throughout the process that will check for any error and report accurately and speedily. There are many different types of sensors, for our application we will inspect three sensors, a magnetic sensor, a through-beam sensor and an IR break beam sensor.

3.1.6.2 IR Break Beam Sensor

The IR Break Beam Sensors with Premium Wire Header Ends from Adafruit, a well-respected American based electronics manufacturer, is a two piece IR beam sensor. There is an emitter and receiver side, the emitter emits a high frequency IR signal that is received by the receiver with a transistor. When the beam is incident the transistor is pulled up to Vcc, when the beam is broken the transistor is turned off making the sensor active low.

Each end of the IR Break Beam Sensor measures 20mm x 10mm x 8mm, and requires 3.3-5.5 V. At 3.3 V the sensor has a maximum range of 25cm when operating at 3.3V and longer when operating at 5.5 V. The emitter consumes 10mA of current when operated at 3.3 V and 20mA of current when operated at 5.5 V. Once the beam is broken, it takes no more than 2ms for a low signal to be output on the output line. The IR Break Beam Sensors are, at the time of writing, readily available for \$2.95 per pair on the Adafruit store front.

3.1.6.3 Through-Beam HiLetgo

The through Beam Hiletgo H2010 sensor is a thin quick response optical sensor. Produced and manufactured by Chinese electronics manufacturer QTai. The sensor has two sides, an emitter which sends out a high frequency IR wave which is received by a BJT transistor. When the beam is incident on the receiver, the BJT is turned on and connects pins three and four. Once the beam is broken the BJT is turned off disconnecting pins three and four. The sensor is often used with a voltage comparator such as the LM393 chip, which is able to send a high voltage signal when the beam is broken to be used as an interrupt signal.

The H2010 optical sensor measures at 27x20x17mm and requires a voltage of 2.8 to 3.5V with an average voltage of 3 volts. While in use it requires 15 mA of current. The emitter and receiver are placed 11mm apart from each other in a U shaped housing. Thus, the sensor can only be used to detect thin objects moving through the beam. Due to using the physics of light and transistors, the sensor has a response time of 15 μ S. The fastest response time out of all the sensors under consideration. The H2010 and the LM393 chips are commonly used and thus are readily available from a variety of different electronics distributors for an average cost of \$1.60 per unit.

3.1.6.4 TLV493D Magnetic Sensor

The TLV493D is a small magnetic sensor in an integrated chip produced by the well-known electronics manufacturer and distributor Texas Instruments. The TLB493D contains three spinning

hall plates in each the X Y and Z directions. When a magnetic field passes over the chip the hall plates each produce a variable voltage which is sent through to a MUX which then sends each signal one by one through an ADC. The ADC sends its output to registers that can be accessed through the I2C Interface.

The TLV493D also has a built in power mode controller that contains a low-power oscillator, basic biasing, accurate reset, undervoltage detection and a fast oscillator. This allows our PCB to be simplified as there is no need for additional circuitry to protect the chip and reduces the possibility of user error in development. Additionally, the Hall plates logic section contains a built in temperature sensor that can shut off the device in the event of a fire, or if the enclosure heats to dangerous levels.

The TLV493D has six pins, a SCL/INT pin for a I2C clock input as well as a Interrupt pin when a reading has been completed. Three ground pins, one Vdd pin, and one SDA pin for I2C data. When operating, the chip requires a voltage between 2.8 and 3.5 V with an ideal operating value of 3.3 V. Underload the chip can consume up to 3.7 mA, with a 25% reduction in current if the temperature sensor section is powered off using I2C. The TLV493D also has the ability to disable the sensors and move to a lower power mode which consumes 7 nA of current.

The TLV493D theoretically has no range, but can detect magnetic fields in quantized units of 98 μ T. Each magnetic field direction has a dedicated 12-bit register, which updates at a frequency of 10Hz when set to ultra low power mode, 100 Hz in low power mode, and 3.3 KHz when filled powered on. Furthermore, the chip can operate anywhere in the temperature range of -40 to 125 degrees celsius. The chip is readily available through Texas Instruments' online site as well as more common chip distributors such as digikey for an average of \$0.81.

3.1.6.5 Sensor Comparison

Selecting the appropriate sensor for the system requires a balance between factors like sensor type, response time, power consumption, detection range, and compatibility with the system's microcontroller. The comparison of various sensors will allow for the most suitable choice depending on application needs such as motion detection, proximity sensing, or magnetic field measurement. The table below provides a side-by-side comparison of the key specifications and features of each sensor under consideration, highlighting their respective strengths and weaknesses.

Table 3-7 Summary of Comparison of Sensors by Authors

	TLV493D Magnetic sensor	H2010 & LM393	IR Break Beam Sensors with Premium Wire Header Ends - 3mm LEDs
Physical dimensions	2.9mmx2.5mm	27x20x17mm	20mm x 10mm x 8mm
Voltage range	2.8 -3.5v	3.3 -5V	3.3-5.5 V
Current draw	3.7 mA	15mA	10-20mA for Emitter 100mA sink for receiver
Sleep/standby power consumption	7nA	15mA	N/A

Detection range (mm/cm)	N/A	10.3mm	25cm
Resolution	98 μ T (resolution)	N/A	N/A
Time to detect an object	10Hz - 3.3 KHz (update rate)	15 μ S	<2ms
Cost	\$0.81	\$1.60 per unit 8 for pack of 5	\$2.95

3.1.7 Photo Sensors

Photo sensors are crucial in applications where light levels, color, or changes in light are used for detecting, monitoring, or controlling various system parameters. These sensors are often used in conjunction with other components, such as LEDs or photodiodes, to measure changes in the surrounding light conditions, detect specific colors, or detect the presence of objects in a particular environment. Photo sensors are commonly used in applications such as light measurement, proximity detection, color sensing, and more.

In this project, we explore two types of photo sensors that will help achieve the goals of detecting subtle variations in light and identifying color patterns on the bills. Specifically, we are considering a sensor for measuring the light passing through or reflected from a banknote and another for detecting the color spectrum of the bill itself.

3.1.7.1 Photo Sensors Used As Light Sensors

One of the other ideas for the mechanism for detecting the orientation of the bill is to use the unique sequence of colors of the bill when scanned horizontally. The sensor needs to be sensitive enough to detect the subtle differences between the types of greens and the subtle hue changes between the different seals on the bill. Furthermore, for the multiple bill detection system, we plan to use an led located behind the bills and use the change in brightness to determine if there are one or more bills in the intake. Thus, we need a sensor that is sensitive, low power, and can detect both amplitude and wavelength of light.

3.1.7.2 TCS34725 Sensor

The first sensor under consideration is the Teleten Robot TCS34725 Sensor. Teyleten Robot is a brand of components founded by the Shenzhen Songhe Technology Co. They are the developers of the MSP32 chip which is used in most Arduino development boards. As such the sensor seamlessly integrates well with any Arduino product with a readily available library. The sensor can be bought for \$9.99 on Amazon for a pack of three for a unit price of \$3.33 or from AliExpress for a unit price of \$2.09. These are cheap when compared to other sensors on the market and thus allow for greater flexibility when allocating costs for other parts.

Referencing the TCS34725 datasheet, it operates with an input voltage of 2.7-3.6v and an operating voltage of the same range as well. The device has the ability to operate in a wait state, which drops current use from 0.235 mA to 0.065 mA which significantly reduces the power. The device will operate in the wait state until a wake command is given over the I2C channel. The time to wake is approximately 2.4 followed by reading and conversion of the light data which takes an additional

2.4 to 614 ms. While fully active, the sensor only requires a max of 1 mW of power. Given the standard wait times, the average current draw can be calculated to be 152 μ A.

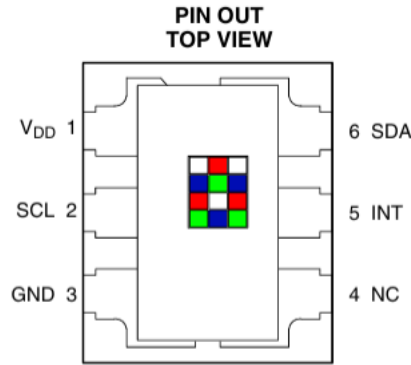


Figure 3-6: Pin Out Top View for TCS34725

The dimensions of the TCS34725 are 20.44mm / 0.8" x 20.28mm / 0.79". The device has 6 pins, VDD, GND, for power SCL, SDA, for the I2C protocol, INT, for interrupts, and NC for no connection, a useless pin. The I2C operates at a standard 400kHz over a two-wire serial bus. The standard I2C bus facilitates easy direct communication to microcontrollers. The active low INT can be programmed to send an interrupt at either an upper or lower threshold and the number of reads past the threshold required to trigger the interrupt to account for noise in the system. A programmable interrupt pin facilitates efficient programming and power use by removing the need to poll the sensor on every clock cycle.

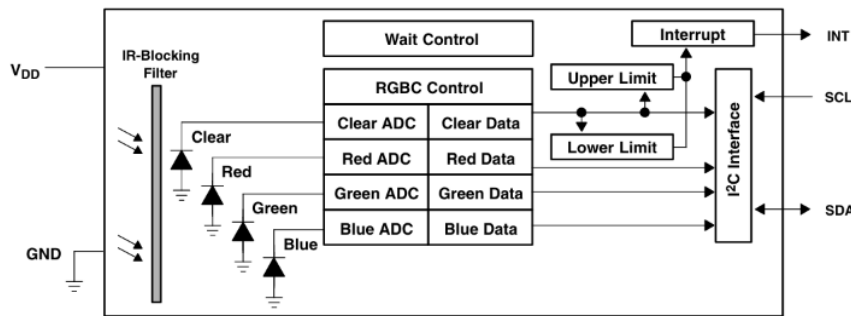


Figure 3-7: Functional Block Diagram of TCS34725

The color sensor contains a three-by-four photodiode array; each row is connected to an analog-to-digital converter that reads the photodiode current, converts the signal and stores it into a data register. The photodiode array is composed of clear, red, blue, and green filtered diodes each coated with an anti-IR filter to reduce unwanted noise. Each ADC congruently converts the associated currents into a 16-bit digital value, which is stored in a double-buffered data register.

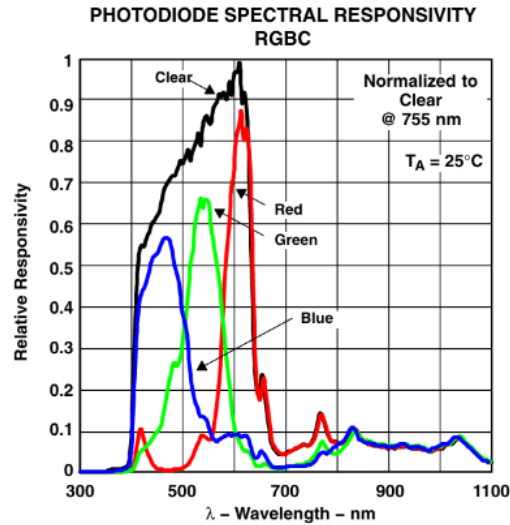


Figure 2

Figure 3-8: PhotoDiode Spectral Responsivity Graph for TCS34725

3.1.7.3 AS7341 11-Channel Light Color Sensor

The second sensor under consideration is the Adafruit AS7341 11-Channel Light / Color Sensor Breakout - STEMMA QT / Qwiic. Adafruit is a USA-based electrical component producer and supplier, all their parts are designed for use with microcontrollers and are built to seamlessly integrate into any project with no trouble. The AS7341 is an 11-channel spectrometer which means it can detect the amount of light along with the different wavelengths of light present as well. The AS7341 can be bought on the STEMMA QT Breakout board allowing for seamless integration with a custom PCB through the standard header. The board can be purchased for \$15.95 per unit across multiple vendors.

Pulling from the datasheet the AS7341 is equipped with 11 channels for measuring light; eight dedicated color channels covering the visual light spectrum, 350 nm to 1000 nm, one covering near-infrared light, NIR, a clear channel for white light, and a flicker channel for detecting lights powered by frequencies ranging 50 Hz to 2kHz. The eight overlapping channels provide a very fine analysis of the present light allowing for detection magnitudes greater than the human eye and far outpacing the other sensors under consideration. The inclusion of an IR sensor not only assists in reducing noise from ambient light but also allows for directional light detection. Furthermore, the flicker channel can be used in combination with other sensors to flag ambient light produced by mains voltage to assist in reducing the chance of false detections.

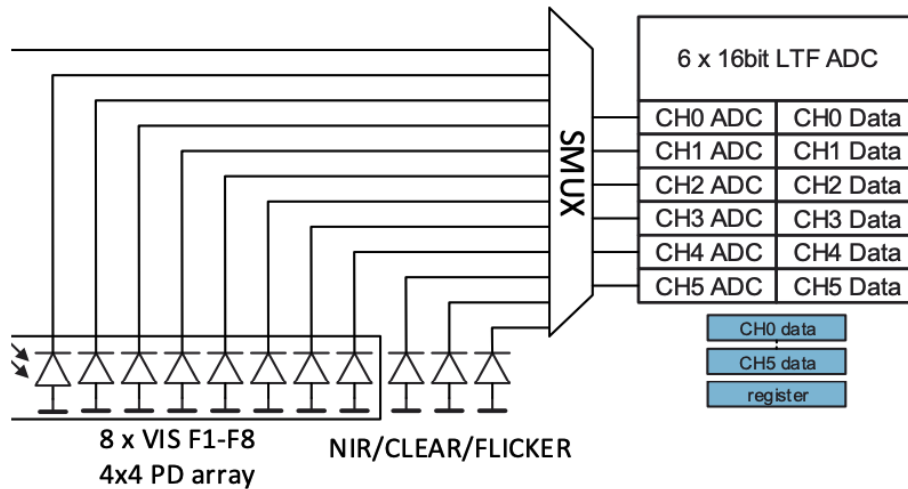


Figure 3-9: Block Diagram of Photodiode Array

The AS7341 detects different colors using high-precision optical filters deposited onto standard CMOS silicon through interference filter technology. The photodetector is composed of eight VIS (visible spectrum) sensors, labeled F1-F8, arranged in a 4x4 photodiode array for detecting visible light. Additionally, the AS7341 includes three extra sensor elements for detecting near-infrared (NIR), clear (broadband), and flicker signals.

Table 3-8 Optical Channel Summary of AS7341

Channel	Center Wavelength [nm] typical	Full Width Half Maximum [nm] typical
F1	415	26
F2	445	30
F3	480	36
F4	515	39
F5	555	39
F6	590	40
F7	630	50
F8	680	52
NIR (Near IR)	910	n/a
Clear	Si response/non filtered	n/a
FD (Flicker Detection)	Si response/non filtered	n/a

The sensor outputs are routed to a Super Mux, which is user-configurable to select six out of the 11 available sensors. The selected sensor signals are then sent to analog-to-digital converters (ADCs), where they are converted into 16-bit digital values. These digital values are stored in data registers, ready for retrieval and further processing.

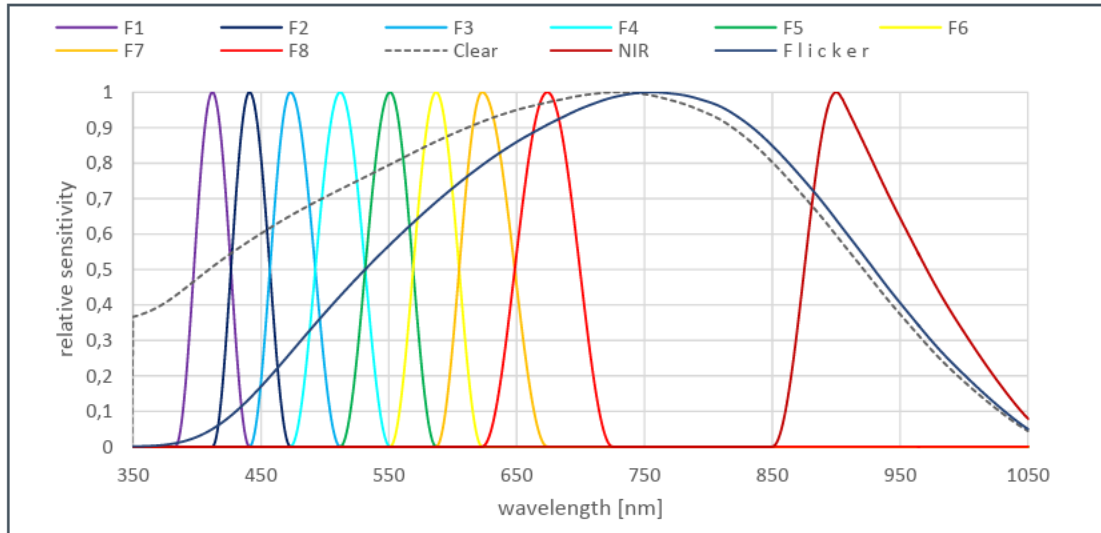


Figure 3-10: Normalized Spectral Responsivity Graph for AS7341

The breakout board contains six accessible pins, VIN & GND for power, SCL and SDA for the I2C communication, INT for interrupts, and a General Purpose Input/Output pin which can be used for a variety of purposes including but not limited to an external trigger input, light sources synchronization output, or as an input for external photodiodes. The interrupt pin can be configured to indicate the status, either ready or busy, of the spectral measurement. It can also be configured to wait for the device from sleep when the light measured falls outside the lower or upper threshold value a variable amount of times. Additionally, the interrupt pin can raise an interrupt when the FIFO buffer is full, when the sensor needs to be re-calibrated when the status register has been updated, when SMUX operation has completed, and when the flicker detector notices a change in the flicker of ambient light.

The AS7341 operates with a standard voltage ranging between 1.7 – 2.0 V and has a typical operating temperature ranging from -30 – 70 degrees Celsius. The AS7341 has three different operating modes to accommodate power savings when the sensor is not actively being read; they consist of Active, idle, and sleep modes. When running at 1.8V, the active mode pulls on average 210 μA up to a maximum of 300 μA , Idle pulls 35 μA on average and up to 60 μA at full load, lastly, sleep mode pulls the least amount only requiring 0.7 μA on average with a maximum current draw of 5 μA when at full load. Thus it can be calculated that at full load the AS7341 can pull up to 600 μW and while sleeping pulls as low as 1.19 μW .

The AS7341 is built for easy integration into the Arduino ecosystem. The board communicates using the standard I2C communication protocol which has ready-use libraries for all Arduino microcontrollers. The AS7341 communicates at a rate of 400 kHz. Furthermore, the board has available libraries for both Arduino IDE as well as CircuitPython. These libraries remove the need for complex register-level programming. This improves code readability which reduces complexity saving on development time as well as improving the maintainability of the program. Lastly, the AS7341 has a footprint of 3.1mm x 2mm x 1mm, the small footprint allows for hassle-free integration into any pre-existing design.

3.1.7.4 TCS230 Color Sensor Kit

The TCS230 produced and developed by TAOS a subsidiary of IBM, is a high-quality industry-level color sensor designed with high reliability and accuracy in mind. TAOS is a well-respected company with decades of experience in developing microelectronics. The TCS230 has two widely available options, the sensor without a lens and one with the lens. Without the lens the component can be bought for \$7.90 from the popular component distributor digikey while with a basic lens the board can be bought for \$9.98 from the online distributor amazon, and with a high end camera quality lens for \$78.50 from the US based company Electronix Express a small division of RSR Electronics a large electronic manufacturer.

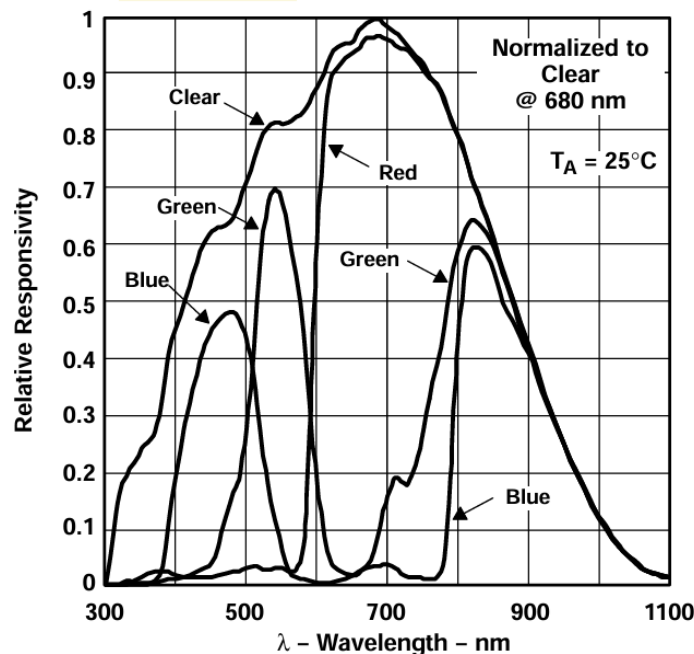


Figure 3-11: Photodiode Spectral Responsivity

The TCS230 uses the TCS3200 color sensing chip. According to the manufacturer the TCS3200 is a high-end eight by eight photodiode array with 16 photodiodes with a red light filter, 16 with a blue light filter, 16 with a green light filter, and 16 with no filter on the photodiode. All four types of filters are interdigitated together to minimize the undesired effects of non uniform incident irradiance, and consequently provide a more accurate color signal. All 16 diodes of the same color filter are connected in parallel and are pin selectable during use. This allows the device to provide “nearly limitless range” of color detection.

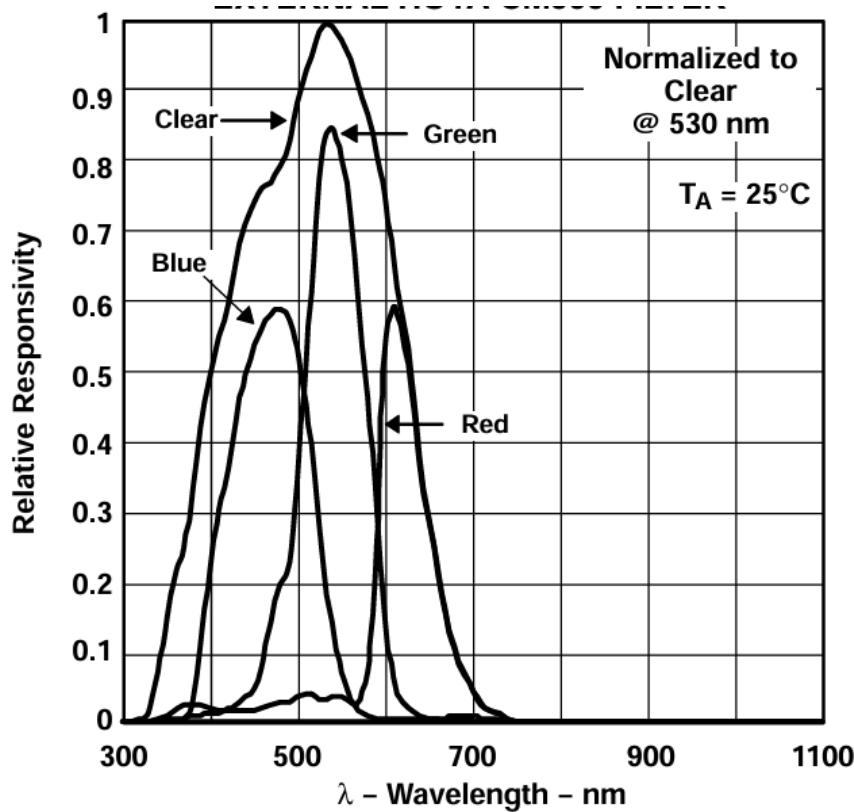


Figure 2

Figure 3-12: Photodiode Spectral Responsivity with External Hoya CM500 Filter

Unlike the other color sensors under consideration for this project, the TCS3200 doesn't output the color detected digitally, but rather encodes the detected light into an analog frequency that then can be directed read using an analog to digital converter on the microcontroller. This results in a resolution that is only limited by the microcontroller. This is accomplished by using a current to frequency converter. Incident light on the diodes produces a variable current corresponding to the wavelength and intensity of the light, then current is conducted to the current to frequency converter where the current is used to produce a variable frequency in the form of a square wave. This signal is then output via the output pin on the chip.

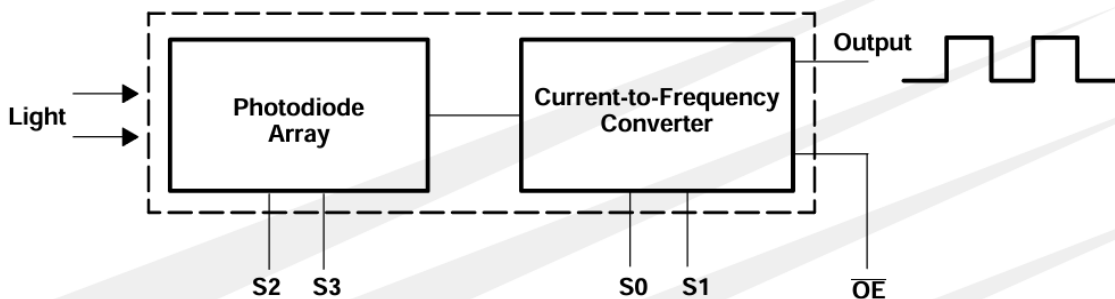


Figure 3-13: Block Diagram of TCS3200

The chip has eight I/O pins, S0, S1, OE, GND, V_{DD}, OUT, S2, and S3. OUT carries the output analog signal produced by the chip, V_{DD} and GND are used for power. S0 and S1 are used to determine the output frequency scaling and powering off the chip. Setting S0 to low and S1 turns the chip, reducing power consumption when not in use. Setting S0 to high and S1 to low scales the output frequency to 2% of maximum frequency of 500 - 600 khz. Setting S0 to low and S1 to high scales the output frequency to 20%, and setting both to high outputs at the maximum frequency. The OE pin, stands for Output enable, and can be toggled to prevent the chip from outputting a signal when not requested, saving power when not needing to read from the chip. S2 and S3 are used to toggle which filtered photodiodes to read from. Setting S2 to low and S3 to low uses the red diodes, S2 to low, S3 to high uses the blue diodes, high low uses the clear filters and high high uses the green filters.

The TCS3200 takes an input voltage in the range 2.7-5.5v, with a typical voltage of 5v dc, takes input current in the range of 2-3 mA when powered on and in the range of 7-15 μ A when powered down. The chip has a typical operating temperature of -40°C to 85°C . The chip has two operating modes that affect voltage use, low level and high level input voltage. When operating at lower level input voltage the chip can reduce the intake voltage to the range 0 to 0.8 volts. While operating at the high level input voltage, the chip can operate from 2-5.5V, with a typical operating voltage of 4.5v. Whether operating at low or high level input voltage, the chip only consumes 5 μ A of current.

The TCS3200 while not specifically designed for compatibility with any particular microcontroller, the open source community has developed an available library that allows the sensor to seamlessly integrate with the arduino microcontroller ecosystem. Additionally the library handles the conversion from analog to digital via software opening up the use of either a digital or analog port on the microcontroller allowing for further customizability when allocating I/O ports. Furthermore, the chip doesn't use either of the two most common communication protocols, I2C or spi. Which helps alleviate congestion on those lines with all the other devices in our system. Lastly the chip has a foot print of 1.15 mm by 1.15 mm, small enough to not cause any issues with integration in our planned foot print.

3.1.7.5 Photo Sensor Comparison

To select the most suitable photo sensor for our application, we evaluated three options: TCS34725, AS7341, and TCS3200. Each sensor has distinct features in terms of spectral range, resolution, power consumption, communication protocol, and ease of integration. The following table summarizes the key specifications and differences among these sensors, providing a basis for determining the best fit for our requirements.

Table 3-9 Summary of Comparison of Photo Sensors by Authors

	TCS34725	AS7341	TCS230
Price (USD)	2.09 - 3.33	15.95	7.90 - 78.50
Resolution	4 16-bits channel	11 16-bit Channels	analog
IR filter	Yes	Yes	No
Dynamic range	3,800,000:1	N/A	N/A
Operating voltage	2.7-3.8V	1.7-2.0V	2.7-5.5V

Current use	2.5 (wait) – 330 (active) μ A	0.7-300 μ A	5 μ A
Communication interface	I2C (400 kbits/s)	I2C (400 kHz)	analog
Response Time	2.4 - 614 ms	27.8ms -738.8ms	100ns
Foot print	2mm x 2.4 mm	6.35mm x 6.35mm x 1mm	1.15 mm by 1.15 mm.
Interrupts	Yes	Yes	No
Color Channel	RGBC	RGBC & NIR & Flicker	RGBC
Ambient Light Sensor	Yes	Yes	No

3.1.8 Material Manufacturing

The selection of an appropriate manufacturing method is crucial for ensuring the durability, stability, and cost-effectiveness of our project. Two primary approaches are available: additive manufacturing (3D printing) and subtractive manufacturing (laser cutting). The choice between these methods depends on the material properties, precision requirements, and structural demands of the final design. This section explores the advantages and limitations of each method.

3.1.8.1 Additive vs Subtractive Manufacturing

Having discussed the individual components, we now turn our attention to the element that ties them all together: the project housing. The housing must be robust enough to maintain its structural integrity over an extended period under normal wear and tear. Additionally, it must provide sufficient stability to withstand the operational effects of the motors within the design.

Considering the constraints of our laboratory resources, skill levels, and budget, three material categories have been identified as suitable for our use case: plastics (such as ABS, PLA, or PETG), wood (such as cedar or plywood), and aluminum. Each material presents unique advantages and limitations, which must be carefully evaluated to meet the requirements of durability, stability, and cost-effectiveness.

Beyond material selection, it is equally critical to determine the appropriate manufacturing method. The decision revolves around whether to employ additive manufacturing using 3D printers or subtractive manufacturing with a laser cutter. Each method offers distinct benefits in terms of precision, scalability, and compatibility with the chosen materials, and the final choice will depend on the specific demands of our project.

3.1.8.2 Additive Manufacturing: 3D printing

3D printing, which utilizes additive manufacturing, constructs objects by layering material sequentially, contrasting with traditional subtractive manufacturing methods. Additive manufacturing builds parts layer by layer by depositing new material, whereas subtractive manufacturing carves out the desired shape by removing material from a solid block.

A 3D printer operates using a heated bed and an extrusion nozzle. It accommodates various materials, from inexpensive prototyping plastics to advanced engineering materials like carbon

fiber, which has been employed in spacecraft by NASA. The material, referred to as filament, is fed into a heating element connected to a smooth metal nozzle. The heating element raises the filament's temperature slightly above its melting point, allowing it to flow through the nozzle. The nozzle's smoothness facilitates laminar flow, ensuring consistent extrusion and preventing microscopic gaps or low-density areas that might compromise structural integrity. Once extruded, the molten filament is deposited onto the build surface, where it cools before additional layers are added. This process repeats until the object is fully constructed.

3D printing offers several benefits over traditional manufacturing techniques such as Computer Numerical Control (CNC) machining or woodworking. Unlike other manufacturing methods requiring specialized skills, 3D printing demands only basic proficiency in Computer-Aided Design (CAD). Filament, the primary material for 3D printing, is affordable, with most types priced between \$10 and \$25 per kilogram. This makes 3D printing significantly cheaper than materials like wood or acrylic.

While 3D printing may take longer to produce parts—typically at speeds of 100 to 150 mm/sec—the process requires minimal human oversight, freeing time for other tasks. Filament is widely available from online retailers and is easy to transport, coming in lightweight, compact spools. Additive manufacturing also allows for intricate designs, including internal holes, unusual geometries, and complex topologies that would be challenging or impossible with traditional methods. Additionally, mid-print pauses enable seamless integration of components, such as magnets, directly into the design.

In terms of safety, most filaments, such as PLA, are non-toxic and safe for indoor use. Other filaments, like ABS or TPU, may emit toxic fumes requiring proper ventilation. Aside from fumes, the primary safety concern involves contact with the hot end, which can reach temperatures up to 240 degrees Celsius and pose a burn risk if touched during operation.

However, 3D printing has notable limitations. Plastics are inherently brittle and weak in both tension and compression, making them prone to breaking under stress. Additionally, plastics are lightweight, which makes them more susceptible to vibrations. In systems like ours, which involve multiple motors generating significant vibrations, this lack of inertia can lead to instability. Vibrations can also cause fasteners, such as bolts, to loosen over time, potentially resulting in catastrophic failure.

Plastic's thermal properties also pose challenges. Common filaments begin deforming at temperatures between 60 and 100 degrees Celsius. Motors, which often operate at similar temperatures, could generate enough heat to compromise the structure's integrity. Furthermore, 3D printers struggle with precision. Standard nozzle sizes and the inherent expansion of extruded plastic limit dimensional accuracy. This results in imperfections such as bulges, gaps, and layer inconsistencies that weaken the structure. Layered construction also creates directional weak points, making printed parts prone to shearing along the filament flow.

Additionally, 3D-printed plastics are difficult to modify post-production. Drilling or creating mechanical linkages can cause structural damage. These factors contribute to a shorter lifespan for 3D-printed parts compared to components made from other materials. This reduced durability can

increase costs, harm consumer perceptions, and negatively impact public relations by making the product appear low quality. Moreover, from a marketing perspective, plastic enclosures are often seen as cheap and fail to convey the sense of quality and reliability that materials like metal or wood provide. These considerations highlight the importance of carefully evaluating 3D printing as a manufacturing method for our project.

3.1.8.3 Subtractive Manufacturing

The other manufacturing method available in our lab is laser cutting, which utilizes a Universal Laser Cutter. Laser cutters are a type of CNC machine that operate using subtractive manufacturing. While additive manufacturing builds objects layer by layer, subtractive manufacturing starts with a larger amount of material and removes portions until the desired part is produced.

Laser cutters remove material using a high-powered laser. Depending on the cutter type, different gases are superheated by passing high-voltage electricity through the laser resonator, producing a specific wavelength of light. This light is directed towards a smooth mirror, which reflects it toward a convex lens. The convex lens focuses the light to a precise point on the material. The concentrated energy generates enough heat to melt or burn through the material. An inert gas, typically oxygen or nitrogen, is pumped in to prevent oxidation or impurities on the freshly cut surface.

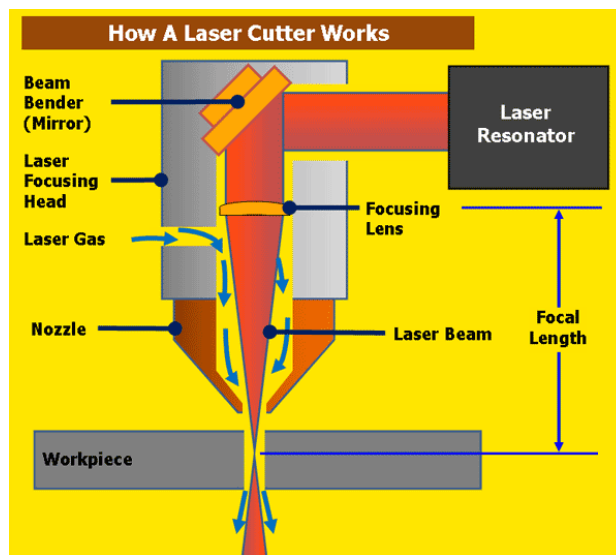


Figure 3-14: Diagram demonstrating the laser cutting process

Laser cutting offers several advantages over 3D printing, starting with precision. While 3D printers are limited by nozzle size and layer height, the Universal Laser Cutter in our lab boasts a precision of ± 0.005 inches—orders of magnitude more accurate than even high-end 3D printers. This precision enables the creation of parts with puzzle-like fits that require no additional tooling.

Another advantage is speed. The Universal Laser Cutter can cut materials like wood and glass at speeds up to 350 mm/s, far surpassing the speed of 3D printers. This makes laser cutting particularly suitable for large-scale manufacturing, which could be valuable if our product gains market appeal.

Laser cutters also accommodate a wider range of materials, including wood, acrylic, and metals, which have different physical properties than the plastics used in 3D printing. This expands the possibilities for component design and increases the structural strength of the final product.

The Universal Laser Cutter in our lab has a work area of 48" x 24" x 12", which is significantly larger than the build volumes of the 3D printers discussed earlier. Like 3D printing, laser cutting is primarily an automated process, requiring minimal human intervention once the design is loaded. This allows engineers to focus on other tasks while the machine operates.

Laser cutters also produce less toxic waste compared to other subtractive manufacturing methods that use chemical coolants. The inert gases used in laser cutting create a safer and cleaner workspace.

Finally, parts created by laser cutting are structurally stronger than those produced via additive manufacturing. Laser-cut parts lack the shear lines created by layered 3D printing. Additionally, laser-cut parts require minimal post-processing: no supports need to be removed, the high-power laser prevents burrs or rough edges, and the precision of the laser eliminates the need for sanding or grinding to achieve tight tolerances.

Despite its many advantages, laser cutting has some limitations. While the 3D printers mentioned earlier can create parts up to 18 inches thick, the Universal Laser Cutter in our lab is limited to cutting materials up to ¼ inch thick. This can be mitigated by layering multiple cut pieces and fastening them together, but doing so introduces structural weak points similar to the shear lines seen in 3D-printed parts.

Another significant drawback of laser cutters is their cost of operation and maintenance. Most 3D printers operate within the 1,000W range, while a laser cutter can require up to 3.8 kW under full load. This results in higher electricity costs, as well as increased expenses for maintenance and replacement parts. This makes laser cutting less feasible during the rapid prototyping phase, where budget constraints must be carefully managed.

Lastly, the safety concerns associated with laser cutting must be addressed. The high-powered laser can cause severe damage to the eyes and skin if direct contact occurs. Users should never place any body part into the work area while the machine is running. Additionally, the laser cutting process generates toxic fumes that can cause serious lung damage if inhaled regularly, as well as particulate air pollution. Proper ventilation is essential to ensure a safe working environment. These safety considerations also raise environmental concerns that would need to be addressed during manufacturing.

3.1.9 Plastic Material

Plastics play a vital role in modern manufacturing due to their versatility, affordability, and ease of processing. With advancements in 3D printing, plastics have become even more accessible for prototyping and production. This section explores different plastic materials considered for the project, analyzing their properties, benefits, and limitations to determine the most suitable option for our design and functional requirements.

3.1.9.1 Plastics Analysis

Plastic is known for its low cost, malleability, and ease of fabrication. Given the nature of our production pipeline, plastic manufacturing will be carried out using additive manufacturing via a Fused Deposition Modeling (FDM) 3D printer. We have access to four different types of printers: the Bambu Lab X1, Delta Maker Tall, Stratasys 270, and Stratasys Dimension Printer. The Stratasys Dimension Printer offers a build volume of 10 x 10 x 12 inches, while the Stratasys 270 has a slightly larger build volume of 12 x 10 x 12 inches. The Delta Maker Tall features a circular build plate with a 9.4-inch diameter and a build height of 18 inches. Lastly, the Bambu Lab X1 Carbon has a build volume of 10 x 10 x 10 inches.

As for the plastic filaments, four types are being considered: Polylactic Acid (PLA), a plant-based plastic; Polyethylene Terephthalate Glycol (PETG), a petroleum-based plastic; Acrylonitrile Butadiene Styrene (ABS), the plastic used in the famous interlocking Lego bricks; and Thermoplastic Polyurethane (TPU), a rubber-like material. Each of these materials has distinct properties, making them suitable for different aspects of the project, depending on the desired performance and application requirements.

3.1.9.2 Polylactic Acid Plastic (PLA)

The first plastic under consideration is PLA. What sets PLA apart from most plastics and all the plastics currently under consideration is the fact that it is plant based. PLA is mainly derived from fermented plant starches from plants like corn, cassava, sugarcane or sugar beet pulp. This makes its properties very different from the other plastics and gives it a unique use case.

Firstly, PLA being produced from agricultural products is significantly cheaper than the other plastics with a kilogram going for a low price of \$6.11 per kilogram on aliexpress at the time of writing, and going for a more expensive average of \$12 per kilogram from more local and reputable suppliers. The cheap cost is evidence of it being easy to produce and source from different suppliers. Additionally, due to being manufactured from renewable sources, PLA is also the most environmentally sustainable out of the plastics under consideration today.

Being made from plants means that PLA is also the least structurally sound of the plastics having the lowest melting points out of the plastics under consideration; PLA melts at a low 150 to 160 degrees celsius, with the smoothest manufacturing occurring at 220 degrees celsius. PLA also is the weakest when it comes to structural strength. PLA has a Tensile strength of 37 Mpa, an elongation of about 6%, a flexural modulus of 4 GPa and a density of 1.3 g/cm³. In more common terms, PLA is useful for decorative items, or items that will under minimal stress. It is not suited for any applications that require small amounts of stress over time or large stresses in short time frames as it will deform if not break into small pieces often releasing particulate matter into the air posing a possible health hazard.

Being constructed from plant matter, PLA is very porous and absorbs moisture quite well. The water can get in between the bonds of the filament and cause the fragment to become very brittle and cause parts to shatter. Additionally, similar effects can be observed when the filament is exposed to UV light such as is commonly emitted by our sun. As such, PLA is very poorly suited to outdoor applications where moisture and UV light is a common occurrence.

Another feature of its plant based construction is its low glass transition point, the point where it starts to deform, of 60 degrees celsius. As such PLA is unsuited for any applications with moderate heat or has significant exposure to the sun or outside applications. This however, makes PLA very easy to work with. Compared to the other materials, PLA is significantly less likely to clog a nozzle, fail to adhere to the print bed, or not stick to the previous layer. This improves prototyping speed as the designer needs to spend significantly less time fiddling with the parameters of the print for each prototype and any issues in manufacturing can be attributed to the design and not the printer.

All things taken into account the average lifespan of PLA in indoor temperature conditions is around two years, when exposed to high amounts of ambient humidity or UV light this can drop to a month, and when held in a climate controlled environment prints can last up to 15 years.

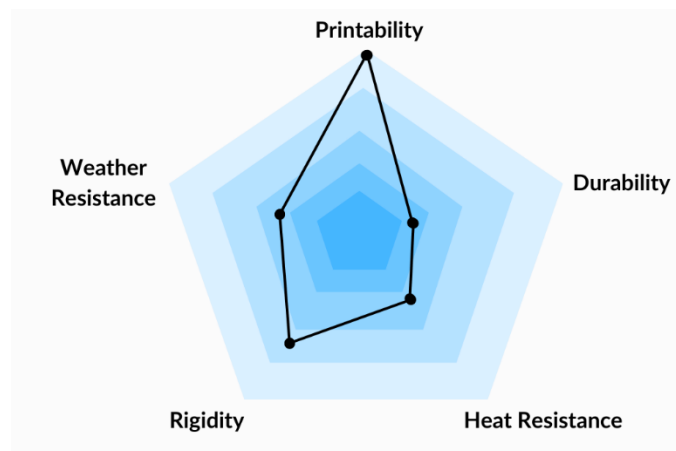


Figure 3-15: Characteristic Pentagon for PLA

3.1.9.3 Polyethylene Terephthalate Glycol (PETG)

The second plastic up for analysis is PETG, derived from petroleum, PETG is significantly stronger than PLA and is the goto for most hobbyists when a strong resilient material is needed. PETG can be sourced from Aliexpress for a slightly more expensive price of \$7.00, or from more local sources for an average of \$15.00 per kilogram at the time of writing. Much like PLA, PETG is readily available and can be sourced from a multiple of manufacturers and online retailers.

Compared to PLA PETG can withstand higher temperatures. PETG has a melting point of 180-230 degree celsius but the best prints can be obtained with a nozzle temperature of 260 degrees celsius. Additionally, PETG typically has a glass transition temperature of 70-78 degrees celsius with some formations reaching as high as 81 degrees celsius. Furthermore, PETG has a water absorption rate of 0.1-3%, significantly lower than that of PLA. In fact with the right settings, one can use PETG to print watertight parts for shallow waters. Furthermore, PETG is moderately UV resistant and can withstand direct sunlight for years without significant loss to structural integrity. This makes PETG uniquely suited for outdoor use where UV rays and high moisture is to be expected.

PETG is also much structurally stronger than PLA. PETG has an Elongation break percentage of 15% compared to PLA's 6%, has a Flexural Modulus of 2.2-2.8 GPa, which means PETG is more likely to flex under stress rather than break and splinter. This increase of strength doesn't come at a cost to weight as PETG still comes in a 1.29-1.4 g/cm³ mating a weight class with PLA. Despite the clear improvements to PLA, PETG has a similar life span of around ~2 years, however that estimate continues for PETG placed in more hazardous conditions such as exposed to high moisture or in direct exposure to UV rays.

PETG has some disadvantages compared to PLA. Firstly PETG is a lot harder to get a successful print. Due to the higher melting point, PETG needs to be printed at a much higher temperature which means the filament takes longer to cool and solidify. This can cause issues for prints, specifically when it comes to the first layer and overhangs. Furthermore, PETG has a more viscous flow when it is conductive to clogs and other issues with the extruder. Thus when printing with PETG, extra care is required when filing in the parameters for the print, and some parts may require more than one print to print correctly. This adds both time and cost to the manufacturing processes.

PETG is produced using petroleum by products, thus its manufacturing is closely tied to the fossil fuel industry. Studies have long since shown that fossil fuels are a strong contributor to climate change, and thus PETG is not as environmentally sustainable when compared to the plant based PLA. Additionally, PETG can takes years to break down in a landfill, though can be chemically broken down into their constituent polymers can those polymers can be used in the production of new PETG or other manufacturing processes.

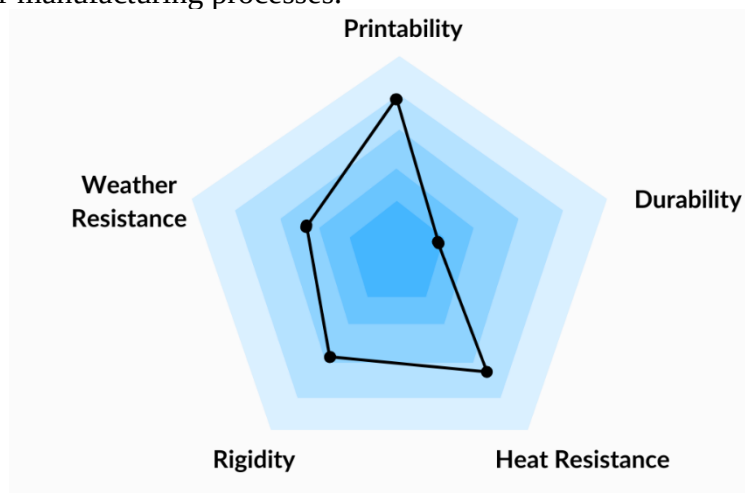


Figure 3-16: *Characteristic Pentagon for PETG*

3.1.9.4 Acrylonitrile Butadiene Styrene (ABS)

ABS is used across the world as the go to plastic when something needs to be produced to be durable and long lasting. ABS can be found in use in the popular lego toys, to outdoor tables, to use in keyboard keycaps, ABS is the plastic of the everyman. ABS has significant advantages when compared to PLA and PETG, however those advantages come at a significant cost.

ABS is much more expensive than the other filaments, it can be found for around \$10.00 on Aliexpress and around \$15.00 on other online retailers. While more expensive, ABS being one of the world's most produced plastics, is readily obtainable and can be sourced from many online

retailers. This price comes with increased strength. ABS has its reputation for a reason, with a tensile strength of up to 60 MPa and an elongation rate of up to 50% this means that ABS can withstand a lot of force. Additionally due to the nature of ABS's construction it is highly resistant to wear and tear. ABS has a water absorption rate of .3%, leading it to be highly resistant to moisture. Additionally, ABS is also highly resistant to both acids and bases, leading to very little breakdown when exposed to pretty much anything. Although ABS is not naturally UV resistant, UV stabilizing additives can be added to the filament to allow ABS to withstand UV rays much better than any other filament under consideration. Most abs plastics outliving humans. ABS has an average lifespan of 50 years but can last much longer if kept in ideal conditions.

ABS is also light. With an average density of 1.11 g/cm³ ABS plastic is the lightest filament under consideration. Because filament is bought by weight this means that you are getting more filament per kilo than any other plastic. Additionally, the low density reduces shipping cost in manufacturing and allows the end product to be more easily maneuvered around. ABS also has the highest melting point out of filaments under consideration. This means ABS has the highest heat resistance. ABS starts to show deformations at 91-100°C the temperature of boiling water. This makes ABS especially useful for construction in electronics where components often reach temperatures approaching 100°C.

Lastly, due to its strength and resilience, ABS holds up very well to many types of post processing that are not possible with the other filaments. One unique type of post processing that is only applicable to ABS is vapor smoothing. By placing any printed parts in an enclosed container above a pool of acetone, the fumes will melt the outside of the printed parts until they smooth into a near mirror finish. This makes ABS capable of being the most aesthetically pleasing out of any of the filaments.

ABS sounds like the perfect filament, however as with anything in engineering, with any benefit comes a cost. ABS is made from crude oil. As such it has a very large negative environmental impact, much larger than PETG. Additionally, printing with ABS produces very toxic fumes that will cause lung damage unless proper ventilation is used and maintained. Even once printed, ABS can still pose a safety risk if it ends up melting due to ambient temperatures or if the part is broken and releases particulates into the air. This means it is very dangerous to sand or use other post processing techniques on ABS parts. All recommended post processing requires the use of hazardous chemicals such as the vapor smoothing using acetone described above.

ABS is also a pain to print. Due to its high elongation rate combined with its large thermal expansion ratio, ABS contracts heavily when cooling. Because 3D printers work by letting molten plastic cool on top of cooled down plastic, this can cause a lot of undesirable effects. Prints can warp and pull themselves off the build plate leading to a lot of failed prints. Additionally, the layers can have a hard time affixing themselves to the previous layer which can either lead to structural weak points where there are gaps between the layers or completely failed prints.

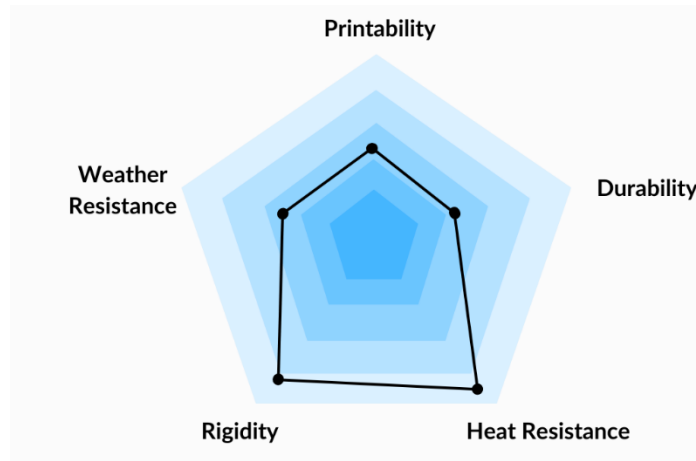


Figure 3-17: Characteristic Pentagon for ABS

3.1.9.5 Thermoplastic Polyurethane (TPU)

The Last plastic under consideration is TPU. Like the other plastics TPU is oil based, but there are bio derived TPUs currently in development. While these TPU's are currently in use in large scale manufacturing, they are not available for use in 3D printing and thus will not be included in our analysis. What makes TPU stand out compared to other types of filament is that it has properties similar to rubber, being a perfect choice for parts that require significant flex.

TPU is more expensive than the other filaments about as expensive as the other specialized filament ABS. A kilogram of TPU filament can be found for around \$13.00 dollars on Aliexpress and around \$20.00 from more local online retailers. TPU filament is heavily used by the hobbyist community when designing parts that need flexibility, thus TPU is readily obtainable and can easily be sourced from a variety of online retailers without any issue.

As mentioned above what sets TPU apart from other filaments is its ability to bend and flex much like rubber, this is due to its very low flexural modulus of 78.7 MPa, which is an order of magnitude smaller than the other filaments under consideration. Helping its flexibility is its elongation rate of 55% the highest seen yet, this comes at a cost with a well below average tensile strength of only 26.0 MPa. TPU falls within the middle of the pack in terms of weight clocking in at a density of 1.22 g/cm³. These make TPU a great choice if one needs to print a custom gasket or a part that is going to be under compression and needs to create a good seal through deformation of the component.

TPU also boasts great layer adhesion. Due to the unique chemical structure of TPU, when printing each layer forms much stronger chemical bonds than other filament types helping to alleviate some of the mechanical concerns regarding the additive manufacturing process. Furthermore, TPU has explicit chemical and UV resistance, able to withstand most common acids and bases while also being able to stand up against constant sun exposure. TPU is also highly resistant to abrasion, which allows parts printed with this filament to be used in high friction environments without concern for wearing through the material with time. These attributes lead to TPU having an above average lifespan with an average TPU component functional for an average of 5 years and the ability to last into the 20s in a climate-controlled environment.

TPU also has its fair share of disadvantages that need to also be considered. Mainly is that much like ABS TPU is highly toxic and needs proper isolation and ventilation before it can be printed. However, unlike ABS, due to its flexibility, TPU is more resilient to wear and tear causing possible harmful particulates being released and posing a health risk to those in proximity to the component. Additionally, until Bio-derived TPU reaches the reliability and quality standards required for mass production, TPU construction requires a large amount of crude oil and thus is a significant contributor to environmental harm.

TPU is also highly hydrophilic, with a water absorption rate of 1.3 %, multiple times greater than any other filament currently under consideration. This means TPU filament requires special storage conditions otherwise the TPU filament might absorb too much moisture and become brittle and unusable for any applications. This attribute continues to the finished product as well. Prolonged exposure to high moisture environments can cause TPU components to warp or expand damaging the structural integrity of the part and can lead to failures.

TPU is also very difficult to print well. TPU is highly abrasive and thus requires specialized equipment such as hardened or volcanic nozzles to print. Furthermore, because TPU is very good at binding to other TPU, it is highly susceptible to clogging nozzles and stringing. Stringing is where after completing a section, the print head moves to another part of the build zone, but the filament does not fully detach from the hot end leading to a thin line of filament connected the hot end to the previous location. Both stringing and clogs can lead to imperfections in prints which have the possibility to cause structural weak points to full on failure of the print wasting filament, time and money. Due to TPU's finicky nature it requires a much slower print speed which will slow down both production and prototyping.

While being resistant to abrasion makes TPU uniquely useful, it also means TPU is resistant to common forms of post processing such as sanding and cutting. A heat gun needs to be used to melt the offending parts back into shape, however this once again runs the risk of exposing engineers to toxic fumes. Furthermore, part of its rubber-like properties TPU is very easy to compress or expand which makes enforcing strict tolerances very difficult with TPU parts. TPU is more ill-suited for any high precise tasks than other similar 3D printed parts.

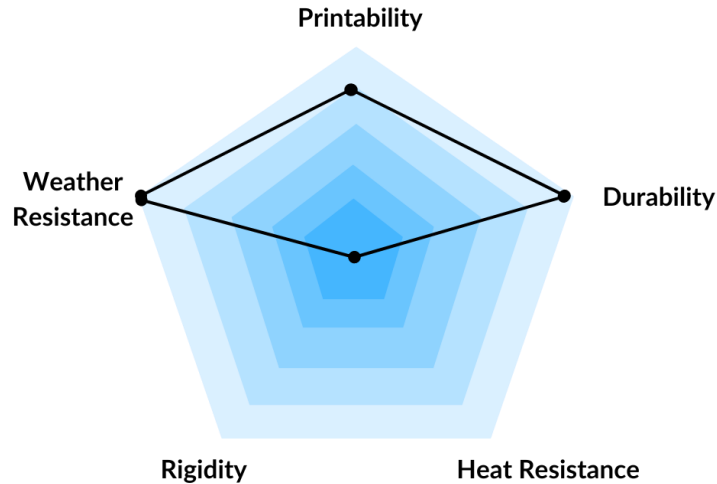


Figure 3-18: Characteristic Pentagon for TPU

3.1.9.6 Comparison of Plastics

Table 3-10 Summary of Comparison of Plastics by Authors

	PLA	PETG	ABS	TPU
Environmental Impact	Low	Mid	High	High
Tensile Strength	37 Mpa,	50-75 MPA	29.8 - 60 MPa	26.0 MPa
Elongation	6%	15%	10 - 50 %	55.0 %
Flexural Modulus	4 GPa	2.2-2.8 GPa	1.6 - 2.4 GPa	78.7 MPa
Weight	1.3 g/cm ³	1.29-1.4 g/cm ³	~1.11 g/cm ³	1.22 g/cm ³
Ease of Machining / Cutting	High	mid	low	Low
Water absorbtion	0.5-0.8 %	0.1-0.3 %	0.3%	1.4%
Glass transition Temperature (degrees C)	60	70-78	105	-30
Cost & Availability	\$6.11-15.00	\$7-20	\$10-25	\$13-25
Lifespan	~2 Years	~2 Years	~50 years	2-5 years
Melting point (Degrees C)	160-220	180-230	200-250	190-250

3.1.10 Acrylic Material

Acrylic is a widely used industrial plastic known for its exceptional transparency, strength, and ease of fabrication. It serves as a viable alternative to glass in many applications due to its impact resistance and significantly lower weight. Acrylic materials are commonly utilized in signage, display cases, protective barriers, and various structural components where transparency and durability are required.

Acrylic's advantages stem from its unique balance of optical clarity, mechanical properties, and chemical resistance. Unlike glass, which is fragile and prone to shattering, acrylic offers a lightweight and shatter-resistant solution. Additionally, its ability to be cut, molded, and shaped with relative ease makes it a popular choice in manufacturing and design.

Despite its benefits, acrylic does come with challenges, including its susceptibility to scratching, sensitivity to high temperatures, and potential release of toxic fumes when burned. The choice between different types of acrylic—cast and extruded—depends on the specific requirements of an application, such as mechanical strength, thermal stability, and manufacturing constraints.

3.1.10.1 Analysis of Acrylic

Acrylics are a form of industrial plastics that are transparent, have outstanding strength, stiffness, and are much easier to manufacture compared to glass or other transparent materials. Acrylics stand out compared to the 3D printing filament plastics mentioned above due to the nature of their construction giving them drastically different properties. The major property of Acrylics that make them valuable in manufacturing is their transparency. While there does exist transparent filament, they are often extremely sensitive to the build environment making failed prints a common occurrence. Additionally, they are prone to errors such as clogs, damaging the nozzle, or not flowing smoothly. Transparency also comes at a cost to structure, with transparent filaments producing more brittle parts. Including a transparent panel or section to the system can assist in identifying faults and also provides a unique aspect that marketing teams can use to push the product.

There are two major different ways of manufacturing acrylics, cast vs extruded. Cast Acrylic is produced through injection molding, where molten plastic is forced into a mold, given time to cool into a solid shape, then removed from the mold for a finished product. Extruded Acrylic in comparison is created by continuously forcing molten plastic through a die which forms the acrylic into a long continuous sheet that is wound up on a spool for further processing.

Similar to the engineering filaments mentioned above, Acrylics are produced using petroleum. As such they have quite a significant environmental impact to consider. However, due to economies of scale, it is cheaper and less impactful to the environment than producing 3D filament. Furthermore, due to the chemicals used in the production of Acrylics, the manufacturing is highly toxic and pose a large danger risk for those producing the Acrylics. While most of the risk is in manufacturing, acrylics can still pose a danger risk for end consumers. If heated, Acrylics can off gas toxic fumes, create internal stress due to thermal expansion that can lead to sudden catastrophic failure causing the part to explode into shrapnel. Furthermore, small acrylic particles are skin irritants and if chronically inhaled can lead to lung cancer. Due to being made primarily of oil, in extreme heat acrylic can catch fire not only providing more fuel to a fire, but also releasing the toxic fumes mentioned above.

These safety concerns make post processing acrylics difficult and require specialized tools and materials. Drilling holes for fasteners requires specialized bits and are prone to causing enough internal stress that the acrylic panel crack or split altogether. Being a plastic, adhesives that chemical bond acrylic to materials such as other plastics and wood exist and can be used to avoid the issues prone with drilling. Furthermore, ¼” acrylics panels can be used with the laser cutter available in our lab, thus allowing for the same precision and design possibilities available with wood.

3.1.10.2 Cast Acrylic (GS)

Cast acrylics have some key benefits over extruded acrylics. First, as cast acrylics are formed using injection molding techniques, this allows the for acrylic to be formed into a larger variety of shapes than extruded acrylic. Additionally, cast acrylic tends to be slightly lighter with an average density of only 1.18g/cm³. However, this comes with a slight structural performance trade off, with cast acrylic having a lower average tensile strength than extruded at 69 MPa before deformation. However, cast acrylic does outperform extruded in impact strength and compressive strength being able to withstand 17 KJ/m² and 124 MPa respectively before deforming. This makes Acrylic much stronger than wood and the 3D filaments cover above.

Furthermore, cast acrylic has an average light transmission rate of 92%, providing the ability to see the inside of the system safely when identifying faults. Furthermore, cast acrylic is designed to withstand temperatures ranging from -40 to 200°C. This is well above and below the rated temperature of any other component in the system and ensures that there is minimum risk of a failure producing enough heat to damage the structure or release the toxic fumes. Lastly Cast acrylic is easily available at any hardware store or from a host of online retailers for anywhere from \$4-18.00 per square foot.

3.1.10.3 Extruded Acrylic (XT)

Extruded Acrylics are very similar to cast acrylics. The major difference is that extruded acrylic cannot be found in the unique shapes that cast acrylics can be produced in. Additionally, because cast acrylic manufacturing process mandates it is produced in small batches they can be produced in a variety of different colors and finishes that extruded acrylic cannot. However, due to the simpler manufacturing process, extruded acrylic can be found cheaper in large sheets and is more easily sourced by end consumers.

Extruded acrylic is slightly heavier than cast acrylic at 1.2g/cm³. Both acrylics are heavier than the other materials considered, this makes them the best suited for dissipating heat and withstanding vibrations produced by the system. Furthermore, extruded acrylic is stronger than cast acrylic when exposed to tensile loads, able to withstand 72 MPa before deforming. However, extruded acrylic is slightly weaker than cast in compressive and impact strength, with an average sheet being able to withstand 117 MPa and 15 KJ/m² of pressure and force respectively before deforming. These parameters far exceed any expected forces produced by our system.

Lastly, extruded acrylic can withstand temperatures ranging from -40 to 70°C. This is significantly reduced compared to the maximum temperature range of cast acrylics and is smaller than the maximum operating temperature of other components in our system increasing the risk of a catastrophic failure. Lastly extruded acrylic can be purchased from some hardware stores or from online plastic retailers for anywhere \$5.00 to \$18,00 per square foot.

3.1.10.4 Acrylic Comparison

Both cast and extruded acrylics offer unique advantages and trade-offs, making them suitable for different applications. Cast acrylic excels in terms of impact strength, compressive strength, and temperature resistance, making it ideal for applications requiring durability and stability under extreme conditions. On the other hand, extruded acrylic offers a more cost-effective solution with slightly higher tensile strength and greater availability in large sheet formats.

While cast acrylic allows for more intricate shapes and a wider range of finishes, extruded acrylic is preferred for applications that require uniform thickness and consistent mechanical properties. The choice between the two depends on factors such as load-bearing requirements, environmental conditions, and cost considerations.

The table below summarizes key differences between cast and extruded acrylic:

Table 3-11 Summary of Acrylic Comparison by Authors

	Cast Acrylic (GS)	Extruded Acrylic (XT)
Density	1.18 g/cm ³	1.2 g/cm ³
Tensile strength	69 MPa	72 MPa
Impact strength	17 KJ/m ²	15 KJ/m ²
Compressive Strength	124 M Pa	117 MPa
Light Transmission	92%	92%
Heat Resistance	-40 - 200 °C	-40 - 70 °C
Cost	\$4.00 – \$18.00 /ft ²	\$5.00 – \$18.00 /ft ²

3.1.11 Wood Material

Wood has been a fundamental construction material for thousands of years, valued for its strength, durability, and natural availability. Unlike synthetic materials, wood is a renewable resource, offering an environmentally friendly option for structural applications. While modern manufacturing has introduced engineered woods and wood-based composites, natural hardwoods and softwoods remain widely used due to their mechanical properties and aesthetic appeal.

In this section, we analyze different types of wood, including both natural and engineered options, to determine their suitability for our project. The discussion includes a comparison of hardwoods and softwoods, an in-depth look at plywood as a versatile alternative, and an evaluation of specific wood types like cedar and cherry. Each material's mechanical properties, cost, ease of processing, and durability will be considered in selecting the best option for our application.

3.1.11.1 Wood Analysis

Moving on to the subtractive manufacturing materials, woods have been used for construction as far back as the stone age. While there does exist wood base filaments, they lack any sort of structural integrity and only exist as a novel way to get a wood like finish and smell to a 3D print and are not in any way viable for professional applications. The two types of wood used for construction are hardwoods such as Cherry, or soft woods such as Plywood or Cedar.

Woods have some significant advantages compared to plastics. Woods are generally more durable, are heavier and thus more resistant to vibrations, more resistant to heat up to a point, and are infinitely renewable. Wood quite literally grows on trees. Plastics that approach the durability and strength of wood are much more expensive than wood. Woods also have a distinct marketing quality. Natural elements often are associated with upper class products, as seen in alcohol and organic food. Having a prominent wood theme in the outside structure of our final product makes the product appear of high quality and can make the consumers superimpose the durable and

reliable qualities of wood onto our product. This can lead to higher sales and public reception when marketing the product.

However, there are also some clear disadvantages. Due to their durability, woods are not as malleable as plastics which limits their ability to be shaped into custom shapes. Woods primarily excel in large flat pieces with minimum angles or thin pieces. Furthermore while plastics will deform and melt when exposed to high heat, wood catches fire. Thus in the unlikely event of a catastrophic failure, wood would continue to escalate the problem while plastics would keep the damage to the surrounding area. Lastly, bearing TPU, most plastics are fairly water resistant. Wood however is extremely hydrophilic and will absorb ambient moisture which can warp or rot the wood.

Wood has unique post processing steps as well. Unlike plastics, wood can be drilled and fasteners can be directly inserted into the wood. This allows for different parts to be attached together more securely than the methods discussed in the plastics section. Additionally once cut, wood filler needs to be used to clean up any holes created in the processing or found naturally in the wood. The wood needs to be sealed and primed in preparing for an outer protective coat. Then the wood must be either stained or varnished depending on the use case. The coat must dry, then sanded back to a smooth finish and repeated until the desired number of coats. This process can take a similar amount of time to the post processing steps required in 3d printing.

3.1.11.2 Hardwoods vs Softwoods

Hardwoods come from angiosperm trees while softwoods come from gymnosperm trees. Hardwoods are generally found in temperate and tropical forests around the world. They have fine veins and has a more complex internal structure than softwoods. This complex structure requires much longer growing time with hards taking up to 150 years before being ready for harvest. This in contrast to softwoods that grow a lot faster than hardwoods, with a harvest time hovering around 40 years. Additionally due to the simpler internal structure and reduced growing time, softwoods are a lot less dense than hardwoods.

Hardwoods internal structure is composed of a large amount of microscopic tubes for transporting water and nutrients. The dense packing of these tubes is what gives hardwoods their rigidity. Softwood in comparison have much larger tubular units with thinner walls used to transport the denser sap.

As mentioned above, due to their more dense internal structures Hardwoods are generally stronger than softwoods. Additionally, they are more durable, have superior fire resistance, and last much longer than softwoods. However, Hardwoods are significantly harder to work with, cost more than softwoods, and due to their long growth time are less environmentally sustainable than softwoods. For our project we will look at four different woods, cedar, softwood, Cherry, hardwood, and plywood both softwood and hardwood versions.

3.1.11.3 Plywood

Plywood is not a natural wood, instead plywood is manufactured from wood waste from other manufacturing processes. The wood waste is compressed into a thin sheet, then a thin layer of adhesive is layered on top. This process is repeated until a desired thickness is reached. Unlike

natural wood, this creates a unique grain pattern, that is the wood doesn't have a uniform grain. A non uniform grain means the wood does not have a weak axis to force. Plywood while weaker than natural woods in a best case scenario, that is when force is applied in the direction of the grain, plywood surpasses natural woods when the force is applied unevenly, randomly, or perpendicular to the grain. The irregular grain structure also means the board is resistant to warping as the grain can not uniformly expand in one direction. The grain also makes plywood resistant to splitting as there is not a defined sheer line for a crack to form.

Plywood, being made from scraps and waste, is very cheap and readily available. At the time of writing softwood plywood can be bought from the local hardware stores for an average of \$1.00-2.00 per square foot of quarter inch plywood. Hardwood plywood can be bought for an average of \$2.00-3.00 per square foot, nearly double that of softwood plywood.

Being made from wood waste means there are a lot of air pockets within plywood. This makes plywood significantly lighter than solid wood. This is beneficial for mobility of the end product, but also makes it easier to handle during the manufacturing stage of development as well. Because plywood is manufactured, it is possible to obtain large sheets that can't be found in natural woods because trees don't grow to those sizes. Lastly, specialized plywood such as exterior or marine grade plywood have been treated to withstand high levels of moisture and outside elements that can help plywood extend their lifespan in exterior applications.

The cheap cost comes with some clear disadvantages. While the low density can be useful in manufacturing. It limits the ability of the plywood to dampen and absorb vibrations and sounds. While plywood can be treated to withstand moisture and high temperatures, it requires significant time and materials in post processing. When accounting for the extra cost it sometimes exceeds the savings and ends up costing more than buying natural wood with those qualities. With proper planning in construction one can ensure that any forces applied to the structure is done in line with the grain, thus making solid wood substantially stronger than plywood.

In terms of safety, the adhesive used in some plywood manufacturing has been shown to be a cancer risk. Furthermore, the porous structure of plywood makes it a very desirable habitat for insects and makes it very susceptible to infestations. Lastly due to the layering process, the layers are clearly exposed to the environment which are prone to a myriad of issues. Firstly, because plywood is constructed out of millions of tiny wood particles it is prone to splinter and can be a safety risk when handling the project. In terms of appearance, the visible layer lines can give a rough unfinished look which could negatively impact public reception of the product. Furthermore, the exposed layer lines can absorb moisture and warp causing the layers to peel away from each other damaging the structural integrity of the final product.

3.1.11.4 Cedar

Cedar is a natural softwood, as such it is more expensive than plywood but not by much. Cedar is normally grown in the western United States and can be sourced from any hardware store for roughly \$3.00 per square foot depending on the quality and quantity of the cut.

Being naturally formed, Cedar contains a lot more empty space than the tightly packed plywood and thus is naturally lighter with density ranging from 310-433 kg/m³. Cedar can be bought via boards of standard sizes hovering around ½" x 1" x 12". Because the grain of the wood runs in a

common direction, Cedar drastically under performs in tensile strength applications when compared to plywood with an average Tensile strength of 1.5 MPa before deforming. However, Cedar outperforms soft plywood in compressive strength due to the common grain providing superior internal support, with the high end cedar able to withstand 43 MPa of compressive pressure before deforming. Lastly Cedar is naturally more elastic than plywood with a modulus of Elasticity of 5.5 GPa.

Cedar is also more moisture resistant compared to plywood maintaining an Equilibrium humidity of only 1.5 to 8%. This makes Cedar more resistant to rot and insect infestations when compared to plywood. Additionally, Cedar has less thermal conductivity than plywood with an average rating of 0.098 W/mK. This makes Cedar less suited to pulling heat out of the system and depositing it into the surrounding than plywood.

Being a natural wood, Cedar doesn't require the extensive post processing that plywood requires to ensure warping and peeling occurs. Cedar being one of the most widely grown trees in the west coast makes it incredibly sustainable and has a negligible environmental impact. Cedar also looks a lot nicer than plywood which can help give the final product a fancy outer appearance that can be used to market the system as more reputable and strongly built. Other than the built in safety risks that come with working with wood such as the sharp tools and dust risk, cedar doesn't have any health concerns that warrant mentioning.

3.1.11.5 Cherry

Cherry is a natural hardwood primarily grown in the north eastern United States making it readily available in any hardware store for around \$20.00 per square foot depending on the quality and quantity of the cut.

Being a hardwood, Cherry has a much tighter cell structure than the other woods under consideration which is shown with its average density resting at 500 kg/m³. The extra density means cherry wood is more structurally sound than the other woods and can more easily transfer heat and withstand vibrations. Much like other natural woods, Cherry wood performs poorly at Tensile strength deforming at only 3.90 MPa. While double Cedar's tensile strength, still pales in comparison to plywood's. However when force is applied against the grain in Compressive strength cherry outperforms all other woods deforming at 49.0 MPa.

Cherry is slightly more hydrophilic than Cedar with an average equilibrium humidity ranging from 6-8%. While not as resilient as Cedar, cherry wood still has a more natural resistance to rot and infestations compared to plywood. Furthermore, being the densest material, Cherry is also the most thermally conductive with a thermal conductivity of 0.144 W/mK. This makes Cedar a great conductor can be best suited for operating in high temperature environments with the proper treatment.

Much like the other natural wood Cedar, working with cherry wood does not introduce any additional safety concerns that do not already exist when working with wood. While still sustainable, Cherry being a hardwood takes an order of magnitude longer than other trees to reach maturity and be ready for harvest. Being a natural wood Cherry also has the benefits of not needing the additional processing steps that plywood requires. It also has the marketing benefits mentioned

in the above Cedar section. Furthermore, consumers often associate weight with quality, Cherry being the heaviest wood under consideration can be used to provide an additional element that can be used to deliver a quality feeling product.

3.1.11.6 Wood Comparison

Each type of wood discussed in this section has distinct advantages and disadvantages that make them suitable for different applications. Plywood offers affordability and structural uniformity, making it a cost-effective and versatile option. Cedar provides natural resistance to moisture and insects, making it ideal for environments with high humidity. Cherry, as a hardwood, delivers superior strength, durability, and heat resistance but comes at a significantly higher cost.

Table 3.11 summarizes the key properties of these wood materials, comparing their mechanical strength, durability, cost, workability, and environmental impact. This comparison will help determine the most appropriate wood selection for our project based on performance requirements and budget constraints.

Table 3-12 Summary of Comparison of Wood Material by Authors

	Plywood (Soft/Hard)	Cedar	Cherry
Density (kg/m³)	400-600 (softwood) 500-800 (hardwood)	310-433	500
Tensile strength MPa	27.6-34.5	1.5	3.90
Compressive strength MPa	31-41.4	2.14-43.0	49.0
Modulus of Elasticity (GPa)	6.96–8.55	5.5	10.3
Equilibrium humidity	12%	1.5-8%	6-8%
Thermal Conductivity	0.13 W/mK	0.0980 W/mK	0.144 W/m-K
Cost	\$1-3.00 /ft ²	~\$2.00 /ft ²	~\$20.00 /ft ²
Workability	easy	easy	Hard

3.1.12 Microcontrollers

Microcontrollers serve as the central processing units for embedded systems, enabling precise control over hardware components. Their selection is critical in ensuring system efficiency, real-time responsiveness, and integration with various peripherals. Given the diverse range of available microcontrollers, choosing the most suitable option requires balancing processing power, memory capacity, connectivity features, and energy efficiency.

This section explores several industry-standard microcontrollers, each with distinct capabilities tailored to different applications. The analysis provides a detailed comparison of their technical specifications, performance considerations, and implementation challenges to guide the selection process for this project.

3.1.12.1 Technical Considerations

A structured evaluation of microcontroller options was conducted to determine the most suitable control solution for the project. Given the vast array of available microcontrollers, the selection process focused on ten industry-standard platforms known for their reliability and widespread

adoption. The evaluation considered key factors such as architecture, bit width, power consumption, memory configurations, and processing capabilities to ensure an optimal balance of performance, efficiency, and scalability.

The control requirements of the project necessitate a comprehensive evaluation of several critical parameters to ensure optimal system performance. A key consideration is the input/output (I/O) interface capacity, as the microcontroller must seamlessly manage communication with multiple peripheral components, including motor control channels, sensor arrays, and illumination systems. Beyond the basic pin count, the evaluation process considered interface protocols, signal processing capabilities, and real-time response performance to ensure effective integration with external devices.

Processing capability was a fundamental criterion in the selection process. The microcontroller must efficiently process real-time sensor data, execute motor control algorithms, and manage overall system states with precision. Both computational power and instruction execution efficiency were thoroughly analyzed to ensure compatibility with the project's workload.

Memory architecture was another critical factor, as the microcontroller required sufficient program memory and RAM to accommodate complex software, buffer sensor data, and maintain system state without introducing performance bottlenecks. The ability to manage data efficiently while maintaining responsiveness was essential for reliable operation.

Power efficiency was also a priority, particularly given the operational constraints of the project. The selected microcontroller needed to balance computational performance with minimal energy consumption, delivering optimal functionality without excessive power draw.

Cost considerations extended beyond the unit price of the microcontroller. Associated expenses, such as development tools, programming hardware, and potential volume pricing implications, were analyzed to ensure economic feasibility while meeting technical requirements.

In addition to technical specifications, the evaluation process accounted for the broader development ecosystem associated with each microcontroller. The availability of robust development tools—including integrated development environments (IDEs), debugging interfaces, and programming utilities—was critical for efficient software development and maintenance. The presence of active developer communities, detailed documentation, and accessible technical support resources was also vital for facilitating rapid development and effective troubleshooting.

Practical implementation factors were carefully assessed, including the physical form factor of the microcontroller, its operating temperature range, and environmental robustness. Compatibility with the intended deployment conditions was a key consideration, as was the scalability of the platform to accommodate potential system expansions or modifications without requiring a complete redesign.

By following this structured evaluation process, the microcontroller selection ensures that the chosen platform meets the immediate technical and operational requirements of the project while

maintaining flexibility for future enhancements. The subsequent in-depth analysis of the ten shortlisted platforms will identify the optimal solution for this specific application.

3.1.12.2 Arduino Uno

The Arduino Uno features an ATmega328P microcontroller operating at 16MHz with 32KB flash memory, 2KB SRAM, and 1KB EEPROM. Its 14 digital I/O pins (6 PWM-capable) and 6 analog inputs provide basic interfacing capabilities. The board includes a USB interface for programming and serial communication, along with an ICSP header for direct firmware updates. The 5V operating voltage makes it compatible with many common sensors and actuators. While the limited memory constrains complex applications, the extensive Arduino library ecosystem and straightforward C++ programming environment make it ideal for prototyping and educational projects.

3.1.12.3 Raspberry Pi Pico

Built around the custom RP2040 microcontroller, the Pico features dual ARM Cortex-M0+ cores running at up to 133MHz. It boasts 264KB of SRAM and 2MB of flash storage, enabling sophisticated multi-threaded applications. The chip includes unique Programmable I/O (PIO) state machines for custom peripheral interfaces and precise timing control. With 26 multi-function GPIO pins, it supports protocols including I2C, SPI, and UART, plus ADC functionality. The MicroPython and C/C++ programming options offer flexibility, though the unique PIO architecture requires specialized knowledge for optimal utilization.

3.1.12.4 ESP32

The ESP32's dual-core Xtensa LX6 processor operates at up to 240MHz, complemented by integrated WiFi 802.11 b/g/n and Bluetooth 4.2 capabilities. It features 520KB SRAM and typically 4MB flash memory, with 34 programmable GPIOs supporting various interfaces including capacitive touch sensing. The chip includes hardware acceleration for encryption, making it suitable for IoT security implementations. Its real-time operating system support enables sophisticated task scheduling, while the integrated wireless stack handles complex networking protocols efficiently.

3.1.12.5 STM32F Series

These ARM Cortex-M based microcontrollers offer diverse configurations, with high-end models reaching 480MHz clock speeds and featuring floating-point units. Advanced peripherals include high-speed USB, CAN bus interfaces, and hardware cryptography accelerators. The series provides up to 2MB flash memory and 512KB SRAM, supporting demanding real-time applications. Notable features include sophisticated timer configurations, DMA controllers, and high-resolution ADCs, making them suitable for industrial automation and medical devices.

3.1.12.6 NodeMCU

Built around the ESP8266 chipset, NodeMCU provides WiFi connectivity with an integrated TCP/IP stack. Operating at 80MHz (boostable to 160MHz), it includes 4MB flash memory and approximately 50KB of usable SRAM. The board offers 11 GPIO pins with PWM, I2C, and SPI capabilities, though some pins serve multiple functions. The Lua-based programming environment

simplifies network application development, while also supporting Arduino IDE integration for C++ programming.

3.1.12.7 Comparison of Microcontrollers 3.1.12.2 – 3.1.12.6

The selection of an appropriate microcontroller requires a structured comparison of key technical attributes, including processing power, memory capacity, I/O capabilities, power consumption, and connectivity options. Table 3.13 summarizes the specifications and distinguishing features of the microcontrollers analyzed in the previous sections. This comparative overview serves as a reference for identifying the most suitable platform based on the project's performance and integration requirements.

Table 3-13 Summary of Microcontrollers 3.1.12.2-3.1.12.6 by Authors

Feature	Arduino Uno	Raspberry Pi Pico	ESP32	STM32F103C8	NodeMCU
Processor	ATmega328P	Dual ARM Cortex-M0+	Dual Xtensa LX6	ARM Cortex-M3	Tensilica L106
Speed	16 MHz	133 MHz	240 MHz	72 MHz	80 MHz
Flash Memory	32 KB	2 MB	4 MB	64/128 KB	4 MB
RAM	2 KB	264 KB	520 KB	20 KB	80 KB
Digital I/O	14	26	34	37	11
Analog Input	6 (10-bit)	3 (12-bit)	18 (12-bit)	10 (12-bit)	1 (10-bit)
PWM Channels	6	16	16	15	11
Communication	UART, I2C, SPI	2×UART, 2×I2C, 2×SPI, USB	UART, I2C, SPI, I2S, CAN	3×UART, 2×I2C, 2×SPI, USB, CAN	UART, I2C, SPI
Operating Voltage	5V (7-12V in)	3.3V (1.8-5.5V in)	3.3V (2.3-3.6V)	3.3V (2-3.6V)	3.3V (4.5-10V in)
Dev Environment	Arduino IDE, PlatformIO	C/C++, MicroPython, Arduino	Arduino IDE, ESP-IDF	STM32CubeIDE, Arduino	Arduino IDE, ESPlorer
Timers	3 (16-bit)	4 (32-bit)	4 (64-bit)	4 (16-bit)	1 (32-bit)
ADC Resolution	10-bit	12-bit	12-bit	12-bit	10-bit
Real-Time Clock	No	Yes	Yes	Yes	Yes
Price (USD)	\$23	\$4	\$8	\$5	\$4

3.1.12.8 Teensy 4.0

Powered by an ARM Cortex-M7 processor running at 600MHz, the Teensy 4.0 delivers exceptional processing capabilities with 1MB RAM and 2MB flash memory. It features 40 digital pins, many supporting PWM output, and 14 analog inputs with 12-bit resolution. Hardware floating-point calculations and SIMD instructions enable complex signal processing applications. The board includes USB host capabilities and multiple hardware serial ports, while maintaining Arduino IDE compatibility through the Teensyduino add-on.

3.1.12.9 MSP430

Texas Instruments' MSP430 microcontrollers excel in ultra-low-power applications, drawing as little as 100 μ A/MHz in active mode and sub-1 μ A in standby. The 16-bit RISC architecture operates at up to 25MHz, with variants offering up to 512KB flash memory and 66KB RAM. Advanced power management features include multiple low-power modes and fast wake-up times. The peripheral set includes high-precision ADCs and sophisticated timer modules optimized for battery-powered applications.

3.1.12.10 SAMD21

This ARM Cortex-M0+ based microcontroller operates at 48MHz with 256KB flash memory and 32KB SRAM. It features a USB 2.0 interface, 6 serial communication modules, and up to 14 analog inputs with 12-bit resolution. The chip includes a hardware divide unit and event system for efficient peripheral management. Its low power consumption and compact form factor target portable applications, while maintaining Arduino IDE compatibility for accessible development.

3.1.12.11 BeagleBone Black

Running a 1GHz ARM Cortex-A8 processor, this single-board computer supports full Linux distributions with 512MB DDR3 RAM and 4GB eMMC flash storage. It features extensive I/O capabilities including 65 GPIO pins, 8 PWM outputs, and 7 analog inputs. The board includes a dedicated PRU microcontroller for real-time operations, HDMI output, and ethernet connectivity. High-level programming support includes Python, JavaScript, and C++, making it suitable for complex embedded computing applications.

3.1.12.12 Arduino Mega 2560

Based on the ATmega2560 microcontroller, this board operates at 16MHz with substantial memory resources: 256KB flash memory, 8KB SRAM, and 4KB EEPROM. Its expansive I/O capabilities include 54 digital pins (15 PWM-capable) and 16 analog inputs. The board provides 4 hardware serial ports for device communication and supports ISP programming. While maintaining the Arduino IDE's accessibility, it adds significant expansion capability through multiple timer/counters, I2C, SPI, and UART interfaces. The robust power regulation system handles input voltages from 7-12V, providing stable 5V and 3.3V outputs for peripheral devices.

3.1.12.13 Comparison of Microcontrollers 3.1.12.8 – 3.1.12.12

The following microcontrollers provide a diverse range of capabilities, from ultra-low-power operation to high-performance computing. Table 3.14 presents a comparative summary of their key attributes, including processing speed, memory capacity, I/O functionality, and power

efficiency. This comparison aids in selecting the most suitable microcontroller for the project's specific requirements, balancing performance, power consumption, and development flexibility.

Table 3-14 Summary of Microcontrollers 3.1.12.8-3.1.12.12 by Authors

Feature	Arduino Mega	Teensy 4.0	MSP430G2553	SAMD21	BeagleBone Black
Processor	ATmega2560	ARM Cortex-M7	MSP430	ARM Cortex-M0+	AM3358 ARM Cortex-A8
Speed	16 MHz	600 MHz	16 MHz	48 MHz	1 GHz
Flash Memory	256 KB	2 MB	16 KB	256 KB	4 GB eMMC
RAM	8 KB	1 MB	512 B	32 KB	512 MB DDR3
Digital I/O Pins	54	40	14	26	65
Analog Input	16 (10-bit)	14 (12-bit)	8 (10-bit)	14 (12-bit)	7 (12-bit)
PWM Channels	15	35	8	12	8
Communication	4×UART, I2C, SPI	8×UART, 3×I2C, 3×SPI, USB	UART, I2C, SPI	6×UART, 6×I2C, 6×SPI	UART, I2C, SPI, CAN, Ethernet
Operating Voltage	5V (7-12V in)	3.3V (5V tolerant)	1.8-3.6V	3.3V (1.6-3.6V)	5V only
Dev Environment	Arduino IDE, PlatformIO	Arduino IDE, PlatformIO	Code Composer Studio	Arduino IDE, Atmel Studio	Debian Linux, Arduino
Real-Time Clock	No	Yes	Yes	Yes	Yes
Price (USD)	\$35	\$20	\$3	\$10	\$55

3.1.13 Drive Belt Material

3.1.13.1 Heat Shrink Tubing

Heat shrink tubing can be used as a belt material by heating it to shrink around pulleys or rollers, ensuring a tight grip. One of its main advantages is that it provides a secure fit, minimizing the risk of slippage. It is also relatively easy to source and can be cut to the required length. However, a major drawback is that it requires a heat source, such as a heat gun or an open flame, for installation, which adds complexity to the assembly process. Additionally, heat shrink tubing is not as elastic as other materials, meaning it may not provide the necessary flexibility for certain machine applications. Over time, it may also wear down or lose its grip, requiring replacement.

3.1.13.2 Polyurethane Tubing

Polyurethane tubing is a common choice for belt applications due to its high flexibility and resistance to wear. It can stretch and maintain tension effectively, making it a good option for power transmission in small machines. One of its major advantages is its durability and resistance to environmental factors such as moisture and chemicals, which makes it a reliable choice for long-term use. However, polyurethane tubing may stretch excessively over time, reducing efficiency and requiring periodic adjustments. Additionally, depending on the thickness and type of tubing used, it may not provide the best grip on smooth surfaces, which can lead to slippage under high loads.

3.1.13.3 3D-Printed TPU Belts

Thermoplastic polyurethane (TPU) belts, when 3D-printed, allow for complete customization in terms of size, thickness, and pattern. This makes them ideal for specialized machines where off-the-shelf belts are not suitable. TPU is highly durable, wear-resistant, and provides good flexibility, ensuring a long lifespan for machine applications. However, 3D printing TPU can be challenging, requiring precise printer settings and material handling to achieve consistent results. The printing process itself can be time-consuming, and for larger or more complex belts, post-processing may be necessary to ensure smooth operation. Despite these challenges, 3D-printed TPU belts offer a tailored and professional solution for machine-building.

3.1.13.4 Thick Rubber Bands

Thick rubber bands are one of the simplest and most cost-effective options for making belts. They are easy to install, provide good elasticity, and offer decent grip for light-duty applications. Because they are readily available in different sizes, they can be a quick and temporary solution for small machines. However, rubber bands have significant drawbacks, including their tendency to degrade over time, especially when exposed to heat, UV light, or repeated stretching. They can snap under excessive tension, leading to machine failure if not replaced frequently. While they may work for low-power applications, they are generally not suitable for long-term or high-load use.

3.1.13.5 Comparison of Drive Belt Materials

Selecting the appropriate drive belt material is essential for ensuring efficient power transmission and machine reliability. Each material has distinct properties that affect its suitability for different applications. Factors such as durability, elasticity, grip, load capacity, environmental resistance, and cost must be considered when making a selection.

The table below provides a comparative analysis of heat shrink tubing, polyurethane tubing, 3D-printed TPU belts, and thick rubber bands based on key performance characteristics.

Table 3-15 Summary of Comparison of Drive Belt Materials by ChatGPT

	Heat Shrink Tubing	Polyurethane Tubing	3D-Printed TPU Belts	Thick Rubber Bands
Cost	\$0.10 - 0.50	\$0.50 - 1.50	\$0.75 - 2.00	\$0.05 - 0.30

Durability (cycles before wear)	~10,000	~50,000	~100,000	~5,000
Flexibility (Shore Hardness A)	90-95	70-85	60-85	50-70
Grip (Friction)	~0.8 - 1.0	~0.4 - 0.6	~0.8 - 1.2	~0.6 - 0.9
Ease of Installation (time in minutes)	3 – 5 (requires heat)	1 - 2	5 – 10 (printing and installation)	<1 (instant)
Suitability for High-Load Applications (Max Load N)	~50 – 100	~75 - 150	~200+	~25 - 50
Customizability	~5%	~15%	100%	~5%

3.1.14 Printer Rollers

3.1.14.1 Printer Rollers vs 3D Printed Rollers

Printer rollers are an ideal choice for use in money machines due to their reliability, durability, and cost-effectiveness. Specifically designed for paper handling, printer rollers are engineered to ensure precise performance, consistent paper feeding, and minimal risk of jams or damage, which is critical in machines that handle currency. These rollers are made from materials optimized for friction and wear resistance, ensuring they can withstand the stress of continuous use in high-speed environments, which is essential when processing large volumes of paper money.

Unlike 3D-printed rollers, which may not provide the same level of quality control or material strength, printer rollers are manufactured to strict standards, offering predictable and consistent performance. 3D printing, while allowing for customization, can sometimes result in surface inconsistencies or durability issues under constant use, especially in high-stress applications like money machines. Moreover, 3D printing requires additional time, specialized equipment, and expertise, whereas purchasing pre-made printer rollers eliminates these complexities and ensures you receive a reliable, tested component.

Considering the cost, time investment, and quality control involved in both options, printer rollers offer a practical, ready-to-use solution for money machines, providing both affordability and reliability without the need for custom fabrication.

3.1.14.2 Ricoh AF03-1081

The Ricoh AF03-1081 roller is highly regarded for its effective paper pickup, providing consistent and reliable performance in handling paper feeding without frequent jams. It is designed to handle a variety of paper types and weights, ensuring smooth operation over time. A key advantage is its durability, which reduces the need for frequent replacements. However, the cost of one Ricoh roller may be higher compared to other options, though it offers long-lasting performance, which can justify the higher price in the long run. If you prioritize longevity and dependable paper handling, this roller is a solid investment, but it may not be the most cost-effective for users needing multiple replacements.

3.1.14.3 Xerox B0CNNHL559

The Xerox B0CNNHL559 roller is another reliable choice for paper pickup. It ensures efficient feeding of paper, reducing the chances of paper jams and enhancing overall printing performance. This roller is designed for moderate to heavy-duty use, providing a solid grip on paper for smooth operation. However, the cost per roller is relatively higher than some alternatives, which could be a disadvantage for those on a tight budget. While the performance is excellent, users may find that the price is not as economical when compared to bulk options, especially for those who need frequent replacements. For those seeking consistent quality and smooth paper handling, the Xerox roller is a good choice, but it may be more expensive over time.

3.1.14.4 HP M402

The HP M402 pickup roller offers good paper pickup capabilities, handling regular printing tasks with ease. It ensures that paper is fed smoothly through the printer, minimizing the risk of misfeeds or jams. The rubber material provides a solid grip, making it ideal for standard paper handling. The advantage of this roller is its relatively moderate price compared to other brands, making it a cost-effective solution for users with regular printing needs. However, while the paper pickup performance is reliable, it may not be as durable as some higher-end rollers, requiring more frequent replacement in high-volume printing environments. The price per roller is reasonable for average users but could add up if used in high-demand situations.

3.1.14.5 HP RF5-3340

The HP RF5-3340 roller is designed for efficient paper pickup, ensuring smooth and consistent feeding without jams. The inclusion of the drive gear helps maintain stable and reliable paper handling, making it a good choice for machines that require precise paper feed mechanisms. The advantage of this roller is its ability to maintain grip on paper under various conditions, reducing the likelihood of slippage or misfeeds. However, this roller’s cost may be higher compared to simpler rollers, particularly because of the additional drive gear feature. While the added drive gear provides extra stability and performance, the price per roller can be a disadvantage for users looking for more economical solutions, especially if the printer does not require such advanced features.

3.1.14.6 Comparison of Printer Rollers

Choosing the right printer roller is essential for ensuring reliable paper handling, minimizing jams, and maintaining consistent performance in machines that process paper, such as money-handling devices and printers. Each roller type varies in durability, grip, cost, and suitability for different workloads. Factors such as material composition, longevity, and price-performance ratio play a critical role in determining the most appropriate option for a given application.

The following table provides a comparative summary of the printer rollers discussed, highlighting their key attributes and trade-offs.

Table 3-16 Summary of Comparison of Printer Rollers by ChatGPT

Criteria	Ricoh AF03-1081	Xerox B0CNNHL559	HP M402	HP RF5-3340
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Price	~\$25 per roller	~\$30 per roller	~\$15 per roller	~\$25 per roller
Size(mm) L x Diameter	25.4 x 38.1	27.6 x 31.1	25.4 x 42.9	29.8 x 45.6
Paper Pickup Quality	Effective, reduces paper jams	Efficient feeding, reduces jams	Reliable, smooth feeding	Stable paper feeding with drive gear
Durability	High, long- lasting	Moderate, durable for heavy use	Moderate, less durable	High, stable with drive gear
Performance	Consistent, good for mixed paper types	Reliable, smooth operation, solid grip	Reliable for standard paper types	Ensures consistency under varying conditions
Grip	Solid, good for a variety of paper weights	Strong grip for smooth paper feeding	Reliable rubber material for solid grip	Strong grip, maintains paper control under varying conditions
Cost Effectiveness	Higher initial cost but long- lasting	Higher cost per roller, may not be economical long-term	Moderate price, cost-effective for regular use	Higher due to drive gear, may be unnecessary for basic applications
Replacements	Fewer replacements needed due to durability	Cost may add up for regular replacements	More frequent replacements may be needed in high-volume use	More expensive due to extra features, may need more frequent replacements if overused

3.1.15 Language Libraries

3.1.15.1 Library Analysis

This section provides a comprehensive examination of Arduino libraries essential for our project's core requirements: stepper and servo motor control, color sensor integration, LED management, and array data manipulation. We evaluated libraries based on their ability to deliver precise motor control for mechanical systems, accurate color sensing capabilities, efficient LED control, and robust data structure handling. Our analysis considered each library's performance characteristics, memory footprint, integration compatibility with our selected microcontroller, and implementation complexity to ensure optimal functionality within our system constraints.

3.1.15.2 Stepper Motor Libraries

1. **AccelStepper:** AccelStepper provides sophisticated acceleration and deceleration profiles while supporting multiple stepper motors simultaneously across various driver types. It's compatible with most Arduino platforms and is optimal for precision movement applications requiring smooth motion profiles, though it requires more computational resources than simpler alternatives.
2. **Stepper:** The standard Arduino library for basic stepper control offers a simpler implementation with a lower memory footprint, limited to basic stepping operations without advanced motion profiles. It features universal compatibility across the Arduino ecosystem and is suitable for straightforward positioning applications where advanced motion control isn't required.
3. **StepperDriver:** StepperDriver is specialized for A4988, DRV8825, and similar stepper driver ICs, providing microstepping control capabilities and support for current limiting features. It integrates well with dedicated driver modules and offers an efficient interface for applications requiring precise control over modern stepper drivers.

3.1.15.3 Servo Motor Libraries

1. **Servo:** The standard Arduino servo library uses Timer1 and supports up to 12 servo motors on most Arduino boards with a simple interface for position control in degrees. It's extensively documented with robust community support, though it may conflict with other Timer1-dependent functions in more complex projects.
2. **ServoTimer2:** ServoTimer2 offers an alternative implementation using Timer2 that resolves Timer1 conflicts with other libraries while maintaining similar functionality. It features a slightly different API from the standard Servo library and has limited compatibility with some Arduino variants but provides a solution for projects with timer conflicts.
3. **ESP32Servo:** ESP32Servo is an optimized implementation specifically for ESP32 microcontrollers that leverages the ESP32's LED PWM controller for improved performance. It supports more servo channels than standard Arduino platforms while maintaining compatibility with the standard Servo library API for seamless migration.

3.1.15.4 LED Control Libraries

1. **FastLED:** FastLED is a comprehensive library for addressable LED control supporting numerous LED types including WS2812B, WS2811, SK6812, and APA102 with advanced color management and HSV color space support. It features efficient memory usage through optimized bit manipulation along with animation helpers, color palette tools, and noise functions, though it has higher processing requirements than simpler libraries.
2. **Adafruit NeoPixel:** The Adafruit NeoPixel library focuses specifically on WS2812/NeoPixel addressable LEDs with a straightforward API and good performance characteristics. It offers lower memory overhead than FastLED for basic applications and is extensively documented with numerous examples, though it provides more limited color manipulation capabilities.
3. **Adafruit DotStar:** Adafruit DotStar is specialized for APA102/DotStar SPI-based LEDs and enables higher refresh rates due to the SPI communication protocol. It has less strict

timing requirements than WS2812 protocols and remains compatible with platforms that struggle with NeoPixel timing constraints.

3.1.15.5 Sensor Libraries

1. Adafruit TCS34725: This interface library for the TCS34725 RGB color sensor employs I²C communication protocol and includes built-in functions for RGB and color temperature calculation. It offers adjustable gain and integration time settings along with interrupt support for threshold-based sensing applications.
2. BH1750: The BH1750 digital light sensor library provides high precision light measurement through a simple I²C interface with straightforward data acquisition methods. It features low power consumption suitable for battery-operated projects and offers multiple resolution modes for adapting to different lighting conditions.
3. AS7341: The AS7341 library supports an advanced 11-channel spectral sensor that provides detailed spectral analysis beyond simple RGB color detection. It delivers high-resolution color discrimination capabilities through an I²C interface with comprehensive data processing functions for specialized color analysis applications.

3.1.15.6 Data Structure and Array Libraries

1. Arduino Standard Array Implementation: The basic C/C++ array functionality built into the language provides static allocation with fixed size at compile time. It offers minimal memory overhead and maximum efficiency but has limited flexibility for dynamic data management scenarios.
2. LinkedList: This dynamic list implementation for Arduino enables flexible memory allocation and deallocation with support for insertion and deletion at any position within the data structure. It requires higher memory overhead than static arrays but proves useful for data collections that need to change size during operation.
3. QueueArray: The QueueArray library provides a specialized implementation of queue data structure with FIFO (First-In-First-Out) data management optimized for sequential processing applications. It excels at buffering sensor readings or command sequences in situations where ordered processing is critical.
4. ArduinoSTL: ArduinoSTL brings a subset of the C++ Standard Template Library to Arduino platforms including vectors, lists, maps, and algorithms for advanced data management. While it causes a significant increase in memory usage, it provides powerful data management capabilities for complex applications on advanced Arduino platforms with sufficient memory resources.

3.2 Part Selection

Selecting the appropriate components for a system is crucial to ensuring reliability, efficiency, and cost-effectiveness. Each part must be evaluated based on its performance specifications, compatibility with other components, and long-term durability in the intended application. This section outlines the reasoning behind the selection of key components, including the power supply, power distribution block, and motors, highlighting their advantages over alternative options. By prioritizing factors such as safety certifications, power handling capabilities, cost-effectiveness, and availability, the chosen components provide an optimal balance between performance and practicality for the project.

3.2.1 Power Supply

The LX60-120500-D1 power supply was chosen due to its balanced combination of reliable performance, safety features, and versatile power delivery. With a 60W power output and a 12V, 5A current rating, it provides ample power for the intended applications, such as LED strips or low-voltage electronics, without the risk of overloading or inadequate performance. While its price is higher than the ANU-090100A and Insignia adapters, its UL-listing ensures it meets rigorous safety standards, offering peace of mind in terms of protection against short circuits and overloads. The compact design (3.1 x 5.1 x 11.7 cm) makes it suitable for tight spaces, and its proven reliability under continuous use, especially in environments demanding consistent power delivery, adds significant value. Furthermore, the LX60-120500-D1's barrel jack connector is a common and reliable connection type, ensuring secure compatibility with various devices. Given its performance, safety, and robust power output, the LX60-120500-D1 was selected as the most optimal choice for the project, prioritizing long-term reliability and safety over the lower initial cost of the other options.

In addition to these technical considerations, the reputation and reliability of the manufacturer, HIT International Consulting, LLC, played a crucial role in the decision-making process. HIT has a well-established history of producing high-quality, durable power supplies, and their commitment to customer support and ongoing product development ensured that the LX60-120500-D1 would meet the demanding needs of the project. The company's solid reputation for providing safe, consistent, and long-lasting products gave confidence that the power supply would perform reliably throughout the project's lifecycle. This additional layer of assurance, backed by the manufacturer's history and commitment to quality, ultimately made the LX60-120500-D1 the most reliable and trustworthy option for this application.

3.2.2 Power Distribution Block

The QBLOK7001 power distribution block from Cabur stands out as an excellent choice due to its optimal balance of performance, cost, and flexibility. With a maximum output current of 63A and a voltage rating of 500V, this distribution block provides sufficient power handling capabilities for most industrial and commercial applications. The seven connection points offer ample flexibility for distributing neutral power across various components, ensuring reliable operation. Its compact size (1.60 x 5.30 x 4.00 cm) allows for efficient installation on DIN rails, helping save space and maintain an organized power distribution system. Priced at \$19.47 for 10 units, it provides a highly cost-effective solution for large-scale projects. Compared to the other options, which feature higher current ratings and fewer ports, the QBLOK7001 strikes the best balance between cost and functionality. With its durability, ease of installation, and overall value, the QBLOK7001 proves to be the most suitable option for reliable power distribution in this setup.

3.2.3 Motors

The G12-N20 Geared Mini DC Motor was chosen for this application due to its optimal balance of torque, power consumption, and precision control. With a wide voltage range of 3-12V, the motor offers flexibility in operation, allowing it to adapt to various power sources while maintaining high efficiency. At full load, the motor delivers up to 16 kg*cm of torque, making it particularly well-suited for applications requiring significant force for precise movements.

Additionally, the low RPM range (50-200 RPM) ensures that the motor can execute tasks with fine control, which is critical for applications like robotics or small-scale actuators that demand accuracy without excessive speed. The motor's robust construction and compact design make it durable and reliable for continuous use in environments requiring minimal maintenance.

Another key advantage of the G12-N20 is its versatility in terms of power consumption. Operating at a low minimum of 42 mW and maxing out at 12W, the motor is capable of operating at different levels of efficiency depending on the load, which helps in optimizing energy use. Its size (36 x 12 x 10mm) and weight (10g) further contribute to its suitability for compact systems that need both power and space efficiency. The motor's affordability, with a price range of \$1.68 to \$15.00, ensures that it remains cost-effective, even for large-scale or budget-sensitive projects. Furthermore, the G12-N20 is more widely available than the other motors ensuring quick procurement facilitating faster prototyping and error correcting if a part were to fail during development. Considering these factors, the G12-N20 stands out as the ideal choice for applications requiring high torque, precision, and flexibility.

3.2.4 Stepper Motor

For the stepper motor, upon evaluating the available options, the 17HS13-0404S1 from StepperOnline was determined to be the most suitable choice. It has a comparable size to the other candidates and falls in the middle of the price range, offering a strong balance between cost and performance. Electrically, it operates at 12 V, making it directly compatible with the existing power supply and eliminating the need for voltage conversion.

As all three motors feature a 1.8-degree step angle, step resolution was not a factor in the selection. While the 17HS13-0404S1 has the highest power draw of the three, this additional power enables it to deliver the highest holding torque at 26 N-cm—an essential characteristic for our application. This torque ensures the rotating plate remains stable under external forces, preventing unintended movement during operation.

Considering its moderate cost, electrical compatibility, superior holding torque, and availability, the 17HS13-0404S1 from StepperOnline was selected for the rotating plate mechanism.

3.2.5 Motor Control Unit

For this project the DRV8912-Q1 Motor control unit was chosen. When normalized for the number of H-bridges, each component averaged the same price. The primary reason of choosing the DRV8912-Q1 comes from prioritizing simplicity over all else. The current system contains a series of motors, sensors, power supplies, regulators, and much more. If the other two ICs were chosen, we would need to incorporate multiple chips in to our PCB. Each board would require its own section on the board, with its own set of resistors, capacitors, LEDs for debugging, voltage and current protection, etc. Each additional component carries a risk of being defective or installed incorrectly adding both cost and development time. Condensing the entire system into a single IC saves on space, cost, and development time making the DRV8912-Q1 stand out.

Furthermore, the DRV8912-Q1 contains a series of additional features that are not provided by the other two ICs. The DRV8912-Q1 contains under and over voltage protection along with over

current protection, further reducing part and space requirements for our PCB. Additionally with a built in PWM system, it frees up the limited I/O on our microcontroller. With increased feature set comes increased complexity. The DRV9812-Q1 is programed via I2C, while the other two ICs are controlled via binary high low. This increased complexity introduces the possibilities for increased errors, however, open-source libraries for the Arduino set of microcontrollers help mitigate this downside.

3.2.6 Sensors

For our application, the combination of the H2010 sensor and the LM393 comparator is the best choice. While we considered other options, including the TLV493 magnetic sensor and IR break beam sensors, the H2010 and LM393 offer the ideal balance of reliability, size, power efficiency, and suitability for our system's requirements.

The TLV493 magnetic sensor detects the magnetic ink embedded in bills to determine their presence. However, our research indicates that this method is unreliable and can be affected by dust and other small particulates. While this weakness can be mitigated by inducing a current in the magnetic ink and sensing the resulting eddy currents—or by using a strong electromagnet—both approaches are impractical for our system, where size and power consumption are critical constraints. Although the TLV493 sensor can uniquely differentiate between a bill and a bill-shaped object, the fine detection it provides exceeds the requirements of our system, as the sensor's primary role is simply to detect the presence of any object.

IR break beam sensors are a more reliable option and are less prone to interference from external magnetic fields. However, they require two separate components: an emitter and a receiver, each with its own power source and housing. Combined, these components occupy more space than either the TLV493 or the H2010 and LM393 combo. The larger size of the IR break beam sensors also gives them a greater detection range compared to the other options. However, this feature is unnecessary in our system, as the bills will pass within a few millimeters of the sensors. Additionally, the larger footprint makes them impractical for a tabletop device, where space is at a premium.

The primary limitation of the H2010 and LM393 combination is the small detection gap, with a distance of only 10 mm between the emitter and receiver. However, since dollar bills are approximately 1 mm thick, this limitation does not affect our application. In every other category, the H2010 and LM393 outshine the break beam sensors. They require only 15 mA of current, have a compact footprint of 27 x 20 x 17 mm, and, as a single sensor, require fewer wires and I/O ports than break beam sensors.

The H2010 also boasts a response time significantly faster than the break beam sensors, with an average response time of just 15 μ S. This speed is critical, as the primary function of the sensors is to halt the machine in the event of a misaligned bill to prevent operational failures.

In conclusion, the H2010 sensor and LM393 comparator combination provides the most efficient, reliable, and practical solution for our system, making it the clear choice for detecting bill alignment.

3.2.7 Photo Sensors

The TCS34725 Sensor is the best choice for detecting the orientation of the bill due to its affordability, low power consumption, and high sensitivity. This sensor is equipped with a three-by-four photodiode array, providing clear, red, blue, and green filtered diodes that can effectively detect subtle color differences on the bill, which is crucial for distinguishing the different seals and hues. With its 16-bit ADC, it can accurately measure light levels and convert them into digital values for precise detection. The TCS34725 also operates efficiently at a low average current draw of 152 μA , making it ideal for battery-powered applications.

Additionally, the TCS34725 offers seamless integration with microcontrollers through the I2C protocol, making it easy to interface with your system. Its programmable interrupt pin helps in reducing the need for constant polling, improving power efficiency. The sensor's ability to operate in a wait state, drawing minimal power, and its fast wake-up time of just 2.4 ms, further contribute to its suitability for detecting subtle changes in light intensity with minimal power consumption. With a unit cost of approximately \$3.33, the TCS34725 offers a cost-effective solution that delivers accurate, low-power light detection for your application.

3.2.8 Material Manufacturing

The decision to use 3D printing (additive manufacturing) for the project's main housing with subtractive manufacturing for additional structure was twofold. First, 3D printing was chosen primarily because of its design flexibility and cost-effectiveness. 3D printing allows for the creation of complex geometries that would be difficult or impossible to achieve using traditional manufacturing methods like laser cutting. This flexibility is particularly important for producing housings with intricate internal features, such as cable channels or mounting brackets, which can be integrated directly into the design. Furthermore, the rapid prototyping capability of 3D printing allows for quick iterations, enabling the team to refine the design efficiently without the need for expensive molds or tooling. This is particularly valuable in the early stages of development, where adjustments and testing are frequent.

In addition to its design advantages, 3D printing offers significant cost savings, especially for small production runs. The material cost of common filaments like PLA, ABS, and PETG is relatively low, and there is no need for specialized equipment or extensive setup, making it an ideal choice for low-volume manufacturing. The minimal waste produced by 3D printing also contributes to its cost-effectiveness, as it only uses the material necessary for building the part. Though 3D-printed plastics may have limitations in terms of strength and thermal resistance, the benefits in terms of ease of production, flexibility in design, and lower costs make 3D printing the most suitable manufacturing method for the project housing.

However, 3D printing has a stigma of being low quality which can negatively affect marketing. Furthermore, 3D printed plastics are lightweight, fragile at the layer lines, and light. To mitigate these concerns, subtractive manufacturing processes using wood and acrylic will be used. These materials are heavier which will help the system dissipate heat and withstand vibrations while also contributing to a better appearance for marketing.

3.2.9 Plastic Material

ABS (Acrylonitrile Butadiene Styrene) was chosen for this application due to its superior strength and durability. With a tensile strength range of 29.8 to 60 MPa, ABS offers excellent resistance to impact and mechanical stress, making it ideal for applications where structural integrity is crucial. This strength, combined with its relatively high heat resistance, allows ABS to perform well in challenging environments, maintaining its shape and functionality even under moderate temperature variations. Additionally, ABS is known for its toughness, which makes it particularly useful in parts that are subjected to physical wear and tear.

Furthermore, ABS is a versatile material, widely used in a variety of industries, from automotive to consumer electronics. Its ease of processing and ability to be molded into intricate shapes adds to its appeal. The material is also resistant to chemicals and has good dimensional stability, ensuring that products made from ABS maintain their accuracy and reliability over time. Overall, ABS's combination of high strength, durability, and adaptability makes it the ideal choice for applications requiring long-term performance under stress.

3.2.10 Acrylic Material

Cast Acrylic (GS) was selected for this application due to its superior mechanical properties and better performance in high-stress environments. While its tensile strength is slightly lower than that of Extruded Acrylic, Cast Acrylic outperforms it in terms of impact strength and compressive strength, making it better suited for withstanding sudden forces and mechanical stress. Additionally, Cast Acrylic can endure higher temperatures, withstanding from -40°C to 200°C, which is significantly higher than the 70°C limit of Extruded Acrylic. This increased heat resistance ensures that Cast Acrylic can maintain its structural integrity in environments with temperature fluctuations, reducing the risk of failure or the release of toxic fumes associated with acrylic materials.

Beyond its strength and temperature resistance, Cast Acrylic's excellent light transmission (92%) makes it ideal for applications requiring transparency, such as panels or sections where visibility is essential. This feature enhances the ability to monitor the system for faults, which is especially useful in maintenance and troubleshooting. Furthermore, Cast Acrylic is widely available and affordable, making it an easy and cost-effective material to source for the project. Its combination of durability, transparency, and heat resistance makes Cast Acrylic the best choice for ensuring long-lasting and safe operation in the system.

3.2.11 Wood Material

Plywood was chosen for this project due to its balanced combination of thermal properties, structural integrity, and sustainability. While thermal conductivity is moderate at 0.13 W/mK, it is still sufficiently effective at diffusing heat without being overly conductive, which could lead to unwanted heat transfer in certain applications. The key advantage of plywood lies in its ability to withstand heat and moisture effectively while maintain a low cost and ease of access. Our system is designed to be used in a professional office environment, which are often climate controlled for the employee's benefits. Thus, the major downsides for plywood being its weakness to ambient moisture, rot and insect infestations are not of major concern.

For the other properties under consideration, plywood outshines both cedar and cherry. Both softwood and hardwood plywood can reach densities higher than cedar and cherry providing more stability for the system. Plywood is also the leader in tensile strength and is middle of the pack for compressive strength. Having a balance of resistance to the two types of forces means the system is more resistant to the types of random forces one can expect from a end consumer.

Moreover, plywood's lightness and easy workability add to its appeal for this project. plywood's density (400-800 kg/m³) and its larger equilibrium humidity make it suitable for diffusing heat in environments that are not subjected to extreme temperature fluctuations. The material's ability to remain stable in humid environments also ensures that it won't deform or weaken over time, providing reliable structural support. plywood's sustainability, readily available nature, and aesthetically pleasing appearance further strengthen its choice, as it offers high-quality, environmentally friendly material that suits both performance and design considerations for foundational components requiring efficient heat management.

3.2.12 Microcontroller

The Arduino Mega 2560 was selected for this project due to its enhanced capabilities while maintaining the Arduino platform's renowned simplicity and accessibility for rapid development and prototyping. The platform's intuitive development environment and straightforward C++ programming syntax, coupled with an extensive ecosystem of libraries, tutorials, and community support, facilitate seamless integration with various sensors and actuators. This makes it an ideal choice for developers seeking efficient implementation without extensive embedded systems experience.

A key factor in choosing the Arduino Mega 2560 is its substantial processing power and comprehensive I/O capabilities. The ATmega2560 processor, operating at 16 MHz, provides robust computational power for managing complex tasks such as motor control, sensor data processing, and peripheral communication. With 54 digital I/O pins (including 15 PWM outputs) and 16 analog inputs, the board offers exceptional flexibility for controlling multiple subsystems within the project.

Furthermore, the Arduino Mega 2560 presents an excellent value proposition. Priced at approximately \$35-40 USD, it offers significant memory resources (256KB flash memory, 8KB SRAM, and 4KB EEPROM) and enhanced I/O options, making it a cost-effective solution for complex projects. The board's power consumption remains efficient at approximately 25-30 mA during active use, ensuring suitability for applications requiring multiple peripherals while maintaining optimal performance. The combination of expanded capabilities, substantial memory resources, and continued ease of use positions the Arduino Mega 2560 as an optimal choice for this project.

3.2.13 Drive Belt Material

Polyurethane tubing was selected due to its high flexibility, durability, and resistance to environmental factors, making it an excellent choice for a variety of small machine applications. One of the key advantages of polyurethane is its ability to stretch and maintain tension, which

ensures effective power transmission and minimizes slippage, even under moderate loads. Its resistance to moisture, chemicals, and abrasion also makes it suitable for use in more demanding environments, ensuring longer-lasting performance. These properties make polyurethane tubing a reliable material for drive belts, especially when the system needs to maintain consistent operation over extended periods.

Moreover, polyurethane tubing provides a good balance between flexibility and durability. It can stretch and conform to the system's needs without excessively stretching or losing its shape, which is crucial for machines that require constant and stable performance. While it may need periodic adjustments as it stretches over time, its overall performance remains stable and efficient in comparison to other materials, such as rubber bands, which can degrade more quickly. Additionally, polyurethane is relatively easy to source and work with, making it a cost-effective solution for most small machine applications.

While there are other materials like 3D-printed TPU belts that offer more customization, polyurethane tubing strikes a good balance between performance and ease of use. It provides sufficient grip and flexibility for most applications without the complexity of 3D printing, making it a practical and dependable option for systems that need consistent, long-term performance with minimal maintenance.

3.2.14 Printer Rollers

The Ricoh AF03-1081 roller was chosen primarily due to its excellent durability, consistent performance, and long-lasting capabilities. This roller offers highly effective paper pickup, which is crucial for maintaining smooth and reliable operation in machines that process large volumes of paper, such as money machines. The Ricoh roller's ability to handle a variety of paper types and weights without frequent jams makes it a highly dependable choice, ensuring minimal downtime and reduced maintenance needs. Its solid grip also reduces the risk of paper misfeeds, further enhancing operational efficiency.

Another significant reason for selecting the Ricoh AF03-1081 roller is its durability. While its initial cost may be higher compared to some alternatives, the long lifespan of this roller makes it a more cost-effective solution over time. With fewer replacements required, the Ricoh roller offers greater value in the long run, particularly in high-demand environments where reliability and reduced maintenance are key priorities. This long-lasting performance justifies the higher upfront cost, making it a sound investment for machines that require consistent and reliable paper handling.

Furthermore, the Ricoh roller's predictable and consistent performance ensures that it meets the strict quality standards required for precision applications, such as in money machines. Its high durability means it can withstand the stress of continuous use in high-speed environments, which is essential when dealing with large volumes of paper money. Overall, the Ricoh AF03-1081 roller provides an ideal combination of performance, longevity, and reliability, making it the best choice for systems that require dependable, high-quality paper feeding.

3.2.15 Language Libraries

The selection of libraries for this project ensures that each component, from motors to sensors to data structures, operates efficiently and effectively, meeting the specific needs of the system. Each library has been chosen based on its ability to fulfill the core requirements of the project, including stepper and servo motor control, accurate color sensing, LED management, and robust data handling. Here's why each library is essential:

1. **Stepper and Servo Motor Libraries:** To achieve precise control over mechanical systems, the project requires two types of motors—stepper and servo motors—each serving a different function. The AccelStepper library is ideal for controlling stepper motors, offering advanced acceleration and deceleration profiles necessary for smooth, controlled movement in applications requiring precision. It allows multiple motors to be controlled simultaneously, making it suitable for systems with multiple axes of motion. The Servo library, while simple, provides reliable control for servo motors, which are often used for position-based tasks. However, conflicts can arise in more complex projects where multiple timer-dependent functions are used. Therefore, the ServoTimer2 library resolves such conflicts by utilizing a different timer, ensuring compatibility while maintaining reliable servo control. ESP32Servo is included because it offers optimized performance for ESP32-based platforms, supporting more servo channels and improving efficiency by leveraging the ESP32's LED PWM controller. These libraries are critical for motor control in systems that require high precision and reliability.

2. **LED Control Libraries:** The project is likely to include addressable LEDs for visual feedback or signaling, which requires specialized libraries for optimal performance. FastLED is a versatile library that supports a wide range of LED types, including the popular WS2812 and APA102, and provides advanced color manipulation, which is essential for creating vibrant displays or signals. While Adafruit NeoPixel is a simpler and more lightweight alternative that also works with WS2812 LEDs, it doesn't provide the same advanced color management as FastLED, making it better suited for less complex applications. However, Adafruit DotStar is included for systems using SPI-based APA102 LEDs, as it allows for higher refresh rates and can handle timing issues more efficiently than the other options. By integrating these libraries, the project can support multiple types of LED configurations with varying complexities, ensuring flexibility and performance.

3. **Sensor Libraries:** Accurate color detection is crucial for the system's functionality, and Adafruit TCS34725 provides an interface for the TCS34725 RGB color sensor. This sensor allows for precise color and color temperature detection, critical for projects that require detailed color analysis. The BH1750 light sensor library provides a different sensing capability, focusing on ambient light measurements. This can be useful for adjusting system behavior based on environmental light conditions, making it a valuable addition for certain sensor-driven tasks. For more specialized applications, the AS7341 library supports an advanced spectral sensor, enabling detailed color analysis beyond basic RGB detection. Its 11-channel sensor is suitable for projects requiring high-resolution color discrimination, expanding the range of possible sensor-driven interactions.

4. **Data Structure and Array Libraries:** Efficient data handling is vital for managing inputs from sensors, controlling motors, and processing commands. The basic Arduino Standard Array

Implementation is included for simple, static data management, offering a low-overhead solution for storing fixed-size datasets like sensor readings or command sequences. For more dynamic data management, the LinkedList library allows the system to manage data that changes in size during operation, such as when new sensor data is added or commands need to be processed sequentially. QueueArray is particularly useful for buffering sensor readings or commands in a first-in-first-out (FIFO) sequence, ensuring that data is processed in the correct order without loss. Lastly, the ArduinoSTL library provides advanced data structures like vectors and maps, which are particularly useful for more complex data management tasks, although it comes with a higher memory cost. These libraries allow the system to handle different types of data efficiently, ensuring smooth operation of the entire system.

Each of these libraries plays a critical role in the project, offering specific functionalities that enable the precise control, sensor integration, and data handling necessary for the system to operate effectively. The combination of libraries allows the project to integrate different components seamlessly while maintaining high performance and flexibility.

Chapter 4 – Standards and Designs Constraints

In any engineering project, adherence to established standards and recognition of design constraints are essential for ensuring safety, reliability, and compliance with industry best practices. Standards define the guidelines that govern component selection, system integration, and operational efficiency, while design constraints dictate the boundaries within which the system must function. These constraints can arise from factors such as cost limitations, material availability, environmental conditions, and regulatory requirements.

This chapter explores the key industrial standards relevant to our project and the various constraints that influenced our design decisions. By following these standards, we ensure compatibility, durability, and performance optimization, while also addressing the challenges posed by technical, financial, and environmental limitations.

4.1 Industrial Standards

Industrial standards provide a framework for the design, manufacturing, and implementation of components and systems, ensuring safety, interoperability, and efficiency. Compliance with these standards is crucial for achieving consistent performance and minimizing risks associated with electrical, mechanical, and environmental factors.

This section outlines the key standards that apply to our project, focusing on motor control, power supply safety, and material specifications. By adhering to these guidelines, we enhance the reliability and longevity of our system while ensuring that it meets industry and regulatory requirements.

4.1.1 Motor Control Design Standards

Stepper and servo motors are critical to achieving the precise speed and torque control required in adjustable speed applications, and their design and operation are governed by well-established industrial standards. In the United States, the National Electrical Manufacturers Association (NEMA) sets detailed guidelines for motor dimensions, cooling methods, and operating conditions, while the International Electrotechnical Commission (IEC) provides complementary global standards. For our project, adherence to these standards ensures seamless integration of motor controllers and reliable performance under variable-speed operation. Specifically, IEC 61800, which governs adjustable-speed electrical power drive systems, is foundational to ensuring accurate control of speed and torque, enabling smooth motion profiles crucial to our system's performance.

NEMA and IEC standards address the physical and operational characteristics of motors used in adjustable speed applications. For example, NEMA ISC 2-1996 specifies that motor controllers, contactors, and overload relays can operate at voltage ratings up to 2000V AC or 750V DC, providing the flexibility required to manage variable-speed drives effectively. Cooling and enclosure standards also play a significant role in adjustable speed systems. For instance, Totally Enclosed Fan Cooled (TEFC) motors, equivalent to IEC IC41, prevent overheating during continuous operation at reduced speeds. Additionally, ingress protection (IP) ratings, such as

NEMA IP55 and IEC IP68, ensure that motors are protected from environmental factors, enabling consistent torque output in various conditions.

Motor design types under NEMA also directly impact the performance of adjustable speed systems. For applications requiring moderate torque with energy efficiency, NEMA Design B motors are ideal, offering normal locked rotor torque and current. High-performance systems demanding high initial torque, such as servo motor applications, benefit from NEMA Design A motors. Furthermore, IEC 60034-1 provides classifications for motor duty cycles, ensuring motors can perform reliably under varying operational patterns. For instance, the S6 duty cycle, which accounts for continuous operation with periodic load variations, aligns perfectly with the needs of our system, where torque demands fluctuate based on load and speed requirements.

By combining NEMA and IEC standards, our project ensures that stepper and servo motors operate efficiently, safely, and reliably in adjustable speed and torque applications. The alignment of physical dimensions, cooling methods, and operational standards guarantees compatibility with controllers while maintaining precision motion profiles. These standards also support long-term reliability and energy efficiency, enabling the motors to deliver consistent performance even in demanding environments. This adherence to industrial standards is critical to the success of our project, ensuring that our system achieves the high level of precision and control required for its intended application.

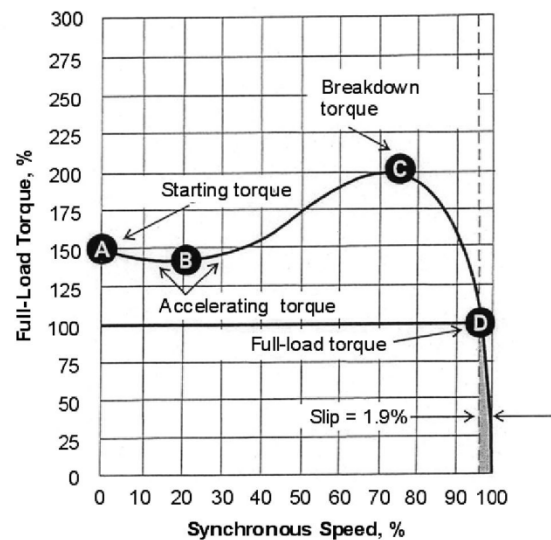


Figure 4-1: Typical Speed/Torque Curve for a NEMA-B Induction Motor

4.1.2 Plastic Testing Standards

ASTM D638 is an essential standard in the world of materials testing, specifically designed for plastics, which focuses on evaluating key properties such as tensile strength, elongation at break, and modulus of elasticity. It outlines the methodology for determining how materials behave under stress, providing a detailed protocol for the mechanical testing of plastic specimens. This standard is widely recognized and utilized across various industries to ensure that materials, especially plastics, meet the necessary strength, durability, and flexibility requirements for their intended applications. For our project, which relies on polyurethane tubing, ASTM D638 is particularly

critical in determining whether the tubing can handle the mechanical loads and environmental factors it will be exposed to during its use. By following this standard, we ensure that the materials selected meet the necessary performance characteristics to maintain the integrity of the system throughout its lifecycle.

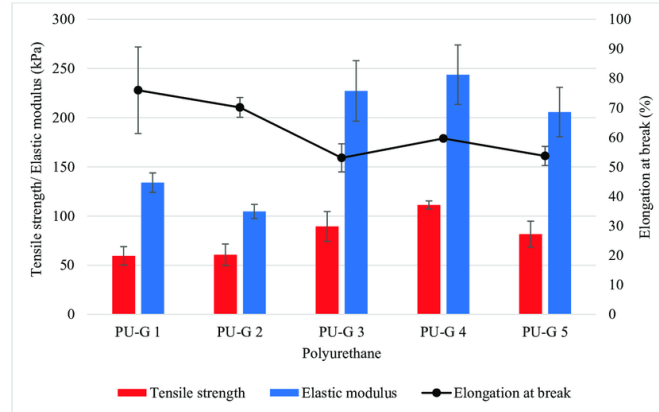


Figure 4-2: *Tensile strength of different polyurethanes produced by different water content*

The testing procedure defined by ASTM D638 involves applying a controlled tensile force to a plastic sample and measuring the deformation or elongation that occurs before the material breaks. These results are vital as they help define the material's ability to withstand forces without failure, such as stretching or breaking under tension. In the context of the polyurethane tubing used in our project, this testing ensures that the tubing can endure repeated stretching or compressing cycles while retaining its mechanical properties. The tubing must not only be strong enough to withstand the mechanical stresses it will encounter but also flexible enough to adapt to the required movement and flexibility within the system. This is especially important in industrial applications where failure due to material shortcomings can have significant consequences.

ASTM D638 also specifies the conditions under which testing should be performed, including temperature, humidity, and the environment in which the material will be used. For example, the standard highlights the importance of testing the material at different temperatures to determine how it will perform under extreme heat or cold. This aspect is particularly important in our project as the polyurethane tubing will be exposed to varying temperatures and environmental conditions that could affect its performance. Whether the material will be exposed to outdoor elements or placed in areas with fluctuating temperatures, ASTM D638 ensures that the selected material will perform as expected, maintaining its strength, flexibility, and overall durability.

Moreover, the standard provides essential insights into the elongation and deformation characteristics of the material under stress. This is critical when evaluating how well the polyurethane tubing will handle dynamic forces such as bending, twisting, or stretching during operation. The results from ASTM D638 will not only confirm the material's ability to endure mechanical forces without failure but will also provide valuable data on how the material behaves under different stress levels. This is important for ensuring the long-term reliability of

the product, as the tubing will need to handle stresses over an extended period without showing signs of fatigue or failure.

In conclusion, ASTM D638 plays a pivotal role in ensuring the material selection for this project is both appropriate and reliable. The standard provides the necessary testing protocols and performance benchmarks that validate the material's ability to withstand the mechanical and environmental conditions it will face. By adhering to ASTM D638, we can be confident that the polyurethane tubing will meet the required strength, flexibility, and durability criteria, ensuring that the final design will be robust and reliable throughout its operational lifespan. This material testing is a fundamental step in meeting the project's engineering and safety standards, contributing to the overall quality and success of the system.

4.1.3 I2C Protocol Standards

In addition to hardware standards that govern physical devices and components, software communication standards such as the Inter-Integrated Circuit (I2C) protocol play a crucial role in the integration of various subsystems within industrial applications. I2C is a widely used communication protocol for connecting microcontrollers, sensors, actuators, and peripheral devices in embedded systems. Developed by Philips Semiconductor (now NXP Semiconductors), I2C operates on a two-wire system—SCL (Serial Clock Line) and SDA (Serial Data Line)—which simplifies communication between devices while minimizing the number of required connections. This makes it particularly valuable in industrial automation, robotics, and control systems where numerous sensors and actuators need to interface with a central controller.

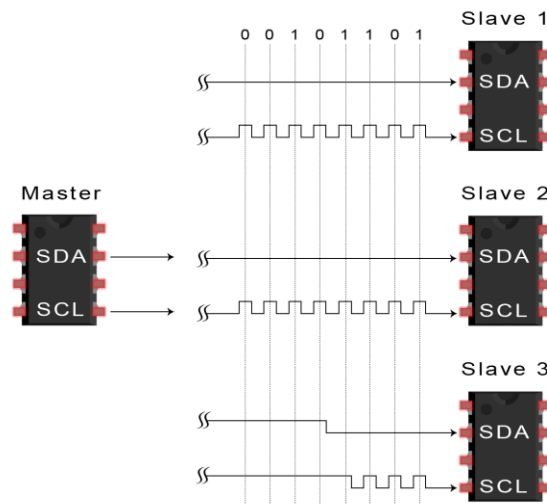


Figure 4-3: I2C Block Diagram

One of the key reasons I2C is popular in industrial applications is its ability to support multiple devices on a single bus. This is accomplished through unique addresses assigned to each device, allowing communication between the controller and peripheral devices such as sensors, motor drivers, and displays without the need for multiple pins or complex wiring. I2C's simple two-wire interface also reduces system complexity and cost, making it ideal for use in resource-constrained environments. For instance, in a motor control system, I2C can be used to interface with sensors for speed or position feedback, as well as control units that manage the stepper or servo motors.

The I2C protocol adheres to several industrial standards, ensuring its reliability and robustness in harsh environments. I2C communication is designed to handle noise and interference commonly encountered in industrial settings. Standardized voltage levels (typically 3.3V or 5V) and built-in features like clock stretching (used to delay the clock signal to allow slower devices to keep up) further enhance its performance in real-world applications. Additionally, the protocol's speed is configurable, with standard mode operating at 100 kHz, fast mode at 400 kHz, and high-speed mode at 1 MHz, giving system designers the flexibility to balance communication speed with noise immunity and power consumption.

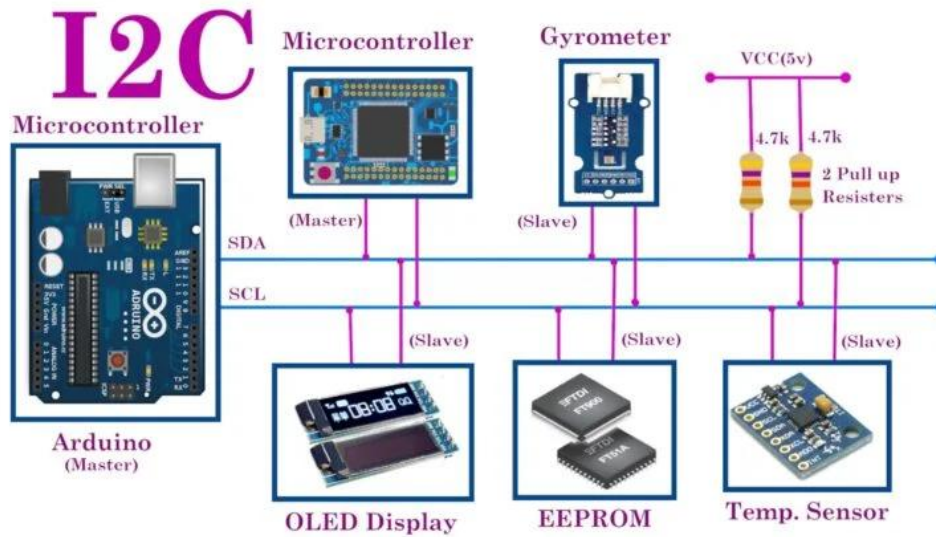


Figure 4-4: Example Diagram of I2C Communication

In industrial motor control systems, I2C enables real-time feedback and precise motor control. For example, a stepper motor controller might rely on I2C communication to receive position data from an encoder or to adjust the motor's speed based on feedback from a tachometer or other sensor. The ability to interface with a wide range of sensors and actuators via I2C ensures that motor controllers can respond dynamically to environmental conditions, improving the overall system's efficiency, accuracy, and safety. Moreover, the use of I2C in industrial motor control aligns with other industry standards such as IEC 61800 (for adjustable speed drives), ensuring compatibility and interoperability between different components in a motor control system.

As industries increasingly embrace automation and Industry 4.0 concepts, protocols like I2C are expected to play a significant role in facilitating communication between distributed systems, ensuring seamless integration, and improving the overall performance of automated processes.

4.2 Design Constraints

Every engineering project operates within a set of design constraints that shape the final product, influencing material choices, cost, environmental impact, and overall system performance. These constraints arise from practical limitations such as budget, sustainability, physical space, and regulatory compliance. Understanding and addressing these limitations is crucial to creating an optimized design that meets project requirements without exceeding available resources.

This section outlines the primary constraints affecting our project, including economic considerations, sustainability efforts, and the trade-offs required to balance performance, efficiency, and cost-effectiveness. By carefully evaluating these constraints, we can make informed decisions that ensure the success of our design while maintaining feasibility within our available resources.

4.2.1 Economic

Given that the group is self-funding the materials, economic constraints remain a critical factor in the design process, particularly since there is no external sponsorship to offset the costs. The budget must be carefully managed, to be kept as low as possible, as every purchase for the project needs to be justified by its necessity and performance impact. A significant advantage, however, comes from the unlimited access to 3D printers available to senior design students, which reduces costs associated with prototyping and part production. By 3D printing parts instead of purchasing pre-made components, the team can allocate funds to more essential areas, such as purchasing specific sensors or motors, while also gaining the flexibility to quickly iterate on design changes.

Even though 3D printing provides some cost relief, the economic constraints still require the group to prioritize parts based on their importance to the project's success. For example, while the 3D printing option may make certain structural parts more affordable, essential components like motors, microcontrollers, and antennas remain a large part of the budget and must be chosen with efficiency in mind. These critical elements must balance cost, performance, and availability, which often involves compromises. For instance, selecting a lower-cost motor with adequate torque and durability might be necessary, but the group has to account for potential limitations in speed or performance that could affect the final outcome.

Additionally, purchasing materials for 3D printing itself adds another layer of consideration. While the cost of filament is relatively low, the quantity and quality of the material needed for specific parts can still be a factor in the overall budget. Moreover, while the ability to prototype and test designs using 3D printed components helps mitigate costs, it also introduces the challenge of ensuring that all printed parts meet the required mechanical properties and tolerances for the project's functionality. As a result, time spent designing, printing, and testing these parts adds complexity to the timeline, as each iteration must be evaluated to ensure it meets the project's performance standards. Balancing these various economic factors will be crucial to ensuring the project stays on track both in terms of budget and timeline.

In conclusion, the economic constraints present a significant challenge to the project, as we are required to make strategic decisions based on budget limitations rather than selecting the most optimal products available. This necessitates careful research and planning to ensure that our choices balance performance and cost while still meeting the core objectives of the project. To mitigate the impact of unforeseen issues, we have allocated a portion of our budget for contingencies, allowing us to replace parts if they malfunction or do not perform as expected. Through thorough design and prudent financial management, we aim to deliver a functional and successful project while adhering to our budgetary constraints.

4.2.2 Sustainability

Sustainability is a key consideration for our project, especially given the growing emphasis on reducing environmental impact and using resources efficiently. Since our group is responsible for purchasing materials as we go, we are mindful of minimizing waste and ensuring that we are selecting materials that are not only cost-effective but also environmentally friendly. One of the primary ways we are addressing sustainability is through the use of 3D printing for parts. The ability to 3D print allows for a more precise use of materials, reducing waste and enabling us to only use what is necessary for our project. Additionally, 3D printing offers the flexibility to modify and iterate on designs without generating excess material waste, as we can reprint parts as needed, rather than relying on traditional manufacturing processes that may lead to more discarded material.

Moreover, sustainability extends to the energy efficiency of our project. By choosing components that optimize power usage, such as the ESP32 microcontroller instead of more power-hungry alternatives, we are helping to reduce the overall energy consumption of the system. This is crucial for the long-term viability of the project, as more efficient systems will not only reduce operating costs but also lower the environmental impact over the life cycle of the project. We are also ensuring that all materials and components used in the project are chosen with sustainability in mind, opting for those that are recyclable or have minimal environmental impact at the end of their use.

Finally, the long-term sustainability of the project relies on its ability to be maintained and repaired. By designing the system in such a way that parts are modular and easily replaceable, we are ensuring that the project can be updated or fixed without needing to discard the entire system. This approach promotes a longer lifespan for the project, contributing to a more sustainable outcome overall. Through careful consideration of these factors, we are striving to create a project that is both environmentally responsible and efficient, aligning with sustainability goals throughout its development and eventual use.

In conclusion, sustainability is an integral aspect of our project, and we are committed to reducing environmental impact through thoughtful material selection, efficient energy usage, and designing for longevity. By leveraging 3D printing technology, we minimize waste and have the flexibility to adjust designs as needed, promoting both cost and resource efficiency. Additionally, careful selection of low-power components and modular design ensures that the system operates efficiently and can be easily maintained or repaired. Through these sustainable practices, we aim to create a project that not only meets our immediate goals but also contributes positively to long-term environmental and economic sustainability.

4.2.3 Health and Safety

Since our project is heavily reliant on mechanical components—particularly motors, actuators, and moving parts—mechanical safety is a crucial aspect of the design and implementation phases. The risk of injury from moving parts, such as motors or mechanical arms, is an immediate concern. To mitigate this, all moving components will be enclosed or shielded with protective casings to prevent accidental contact. For example, any gear mechanisms, rotating motors, or other

potentially hazardous parts will be housed in sturdy, durable casings to ensure that users cannot come into direct contact with them during operation.

Additionally, safety barriers or guards will be implemented where necessary to shield users from rotating or actuating parts, and components will be mounted securely to avoid any unexpected detachment or failure. It is crucial that any mechanical joints, pivots, or actuation points be properly designed to reduce the likelihood of malfunction or failure that could cause injury. We will be paying close attention to the stress points on these components, ensuring that they are adequately reinforced to handle the expected load without risk of breakage.

Another safety measure involves ensuring that any moving parts are properly aligned and balanced, reducing the likelihood of erratic motion or mechanical instability. For instance, motors and actuators will be tested for performance under load conditions to confirm they are operating within safe limits. Additionally, the system will include built-in fail-safes such as emergency stop mechanisms to prevent uncontrolled movement in the case of a malfunction.

Finally, we will adopt best practices for handling and assembling mechanical parts. This includes proper tools for assembly, the wearing of personal protective equipment (PPE) such as gloves and safety glasses, and following safe procedures during testing to minimize any risk of injury to the team. Clear safety signage and warnings will be placed around the workspace to ensure that all individuals are aware of potential risks associated with the mechanical components during both development and operation.

While the project is mechanically focused, electrical safety remains an essential consideration due to the use of electrical components like motors, microcontrollers, and sensors. To prevent electrical hazards, we will ensure that all wiring is properly insulated and secured. Electrical connections will be clearly labeled, and components will be chosen to meet or exceed necessary voltage and current ratings to avoid overheating or short-circuiting. Proper grounding techniques will be used throughout the system to ensure that any stray electrical currents are safely directed away from sensitive components and users.

Moreover, all electrical components will be housed in protective enclosures to prevent exposure to water or dust, which could cause electrical faults or even electrical shock. For parts that require user interaction, such as buttons or switches, we will design them in a way that minimizes electrical exposure to the operator. Safety features like circuit breakers, fuses, or emergency power-off switches will also be implemented to ensure the system can be deactivated safely in case of malfunction.

In summary, the primary concern for our project's safety revolves around the mechanical aspects, with a focus on protecting users from moving parts, ensuring the structural integrity of components, and mitigating risks during testing and operation. However, electrical safety will still play a significant role in preventing hazards related to wiring, power surges, and faulty connections. By ensuring that both mechanical and electrical components are carefully designed, enclosed, and properly tested, we aim to create a safe system that reduces risks for both the development team and any users interacting with the system.

4.2.4 Environmental

Environmental considerations are crucial in the design and execution of our project. We aim to minimize the environmental impact through energy efficiency, material sourcing, and waste reduction. One key aspect is optimizing energy consumption, especially for motors and sensors, by selecting energy-efficient components and incorporating power-saving features like automatic power-down modes.

As we are 3D printing parts, we will use eco-friendly materials like PLA and PETG, which are biodegradable or recyclable. We will also minimize material waste by using only what is necessary and ensuring proper disposal. The durability and longevity of the system will be prioritized to reduce waste, using high-quality, repairable parts where possible.

Lastly, the system will be designed to be robust and resistant to environmental factors, ensuring minimal maintenance and extending its lifespan. This will reduce the need for replacements and further waste. By focusing on these environmental aspects, we aim to create a sustainable and efficient system that aligns with best practices.

4.2.5 Social

The social impact of our money sorting machine is significant, as it addresses the common challenge of manually organizing and sorting currency. This task is time-consuming and error-prone, particularly for businesses, financial institutions, and individuals dealing with large amounts of cash. By automating this process, our machine can save time, reduce human error, and improve overall efficiency in cash handling.

Furthermore, the machine has the potential to improve accessibility for people with disabilities or those who may find manual bill sorting physically challenging. The ease of use and user-friendly interface ensure that a wider demographic can benefit from the technology.

On a broader scale, the money sorting machine may contribute to reducing human labor in tasks that are often repetitive and mundane. This could lead to a shift in how people perceive cash handling jobs, encouraging more efficient practices within financial institutions and retail settings. Additionally, by reducing errors in cash sorting, the machine can help mitigate instances of fraud or miscounting, which has a positive social effect on both businesses and consumers.

Ultimately, the social benefits of this product go beyond mere convenience—it can foster greater efficiency and accessibility in the financial and retail sectors, benefiting both businesses and individuals.

4.2.6 Political

The political impact of our money sorting machine is closely tied to its potential integration into the banking system. As financial institutions continue to modernize their processes, governments and regulators are placing more emphasis on streamlining cash management and improving operational efficiency within banks. Our machine aligns with these goals by offering a reliable, automated solution for sorting bills, which can reduce human error, improve security, and enhance the overall speed of transactions.

Moreover, the adoption of such technology within banks could help ensure compliance with regulations related to anti-money laundering (AML) and combating the financing of terrorism (CFT). By automating the sorting process, the machine can aid in detecting counterfeit bills and reduce the potential for illegal activities, ensuring that banks maintain a high level of trust with their customers and regulators.

On a larger scale, the political landscape also influences the adoption of cash handling technologies, as governments aim to reduce the burden on public sector workers and improve the efficiency of government-run institutions. If our machine is adopted by governmental financial bodies, it could become an essential tool in reducing the cost of managing physical currency, which is often a significant concern for central banks.

Overall, the political implications of our money sorting machine center around its potential to support the banking system's modernization efforts, aid in regulatory compliance, and improve the efficiency of currency handling in both public and private financial institutions.

4.2.7 Ethical

The ethical implications of our money sorting machine are primarily centered around its impact on labor and privacy. While automation can increase efficiency and reduce human error, it also raises concerns about job displacement, particularly in environments where cash handling is a significant part of the workforce, such as retail or bank branches. As we design this machine, we need to consider how it might affect workers who traditionally handle cash sorting and whether it will lead to job loss or if it will create new roles in overseeing and maintaining automated systems. Ethical considerations must also involve offering retraining opportunities to workers whose tasks may become automated.

Additionally, there are privacy concerns surrounding the handling of physical currency, especially in contexts where the machine might store or process sensitive information, such as when it's used in financial institutions or government sectors. The sorting machine must be designed to ensure that no unauthorized access is allowed to any data associated with the bills, and that any tracking or data collection respects privacy laws and regulations. Moreover, counterfeit detection features must be implemented ethically, ensuring that customers' privacy is maintained without unnecessary surveillance.

Ethically, we must also address the environmental implications of using such machines, ensuring that the materials used are sustainably sourced and that the machine can be recycled properly at the end of its life. Designing with sustainability in mind not only helps minimize environmental impact but also aligns with corporate social responsibility practices, which are increasingly important to both consumers and businesses.

Ultimately, the ethical considerations for this project involve balancing the benefits of automation and efficiency with the need to safeguard jobs, ensure privacy, and minimize environmental impact. These principles will guide the development of the money sorting machine in a way that maximizes its positive impact on society.

4.2.8 Manufacturability

The manufacturability of our money sorting machine is a critical constraint, as the design must be optimized for efficient and cost-effective production. Given the limited budget for the project, it is essential to ensure that the materials and components selected are not only high-quality but also readily available and affordable. The use of 3D printing for some parts is advantageous, as it allows for rapid prototyping and customization while minimizing the cost of producing specialized components. This also offers flexibility in design iterations, allowing us to refine the machine's functionality and form before committing to more expensive manufacturing methods.

However, the complexity of assembling a mechanical system with various moving parts, sensors, and electrical components means that attention to detail is needed to ensure that all parts fit together seamlessly during the manufacturing process. Sourcing the right components, such as motors, sensors, and electronic boards, must be done with care to ensure compatibility and ease of assembly. Additionally, the cost of producing these parts must be balanced against the overall budget, ensuring that the machine remains economically viable while maintaining quality standards.

Manufacturability also involves considering the ease of assembly, testing, and repair. The design should allow for straightforward assembly processes, with clearly defined steps and minimal specialized equipment needed. If the machine requires complex or time-consuming assembly, it could increase production costs, which may exceed the available budget. Additionally, considerations for long-term maintenance, such as easy access to internal components for repairs or upgrades, should be incorporated to ensure the product's longevity and user-friendliness.

In summary, to address manufacturability, we must focus on producing a product that can be built efficiently with available resources, keeping costs under control while ensuring the quality and functionality of the machine. Careful planning and design choices, such as leveraging 3D printing and selecting compatible components, will be key to ensuring that the money sorting machine can be manufactured within the project's constraints.

Chapter 5 – ChatGPT and Other AI Platforms

The most critical component of this project is the sensor used to determine the orientation of the bill. Multiple methods were considered to detect orientation, including using a small camera with modern computer vision processing, employing a color sensor to generate unique color signatures for each orientation of the bill, and utilizing sensors to detect the unique security features found on each side of the bill.

Given the current emphasis on AI and machine learning, we initially believed that incorporating AI into the product would not only make it more marketable but also allow us to gain valuable skills relevant to the industry. Consequently, our first option under consideration was to use computer vision to determine the bill's orientation. The approach would focus on the software and photonics aspects, with a team composed solely of computer engineers and photonics engineers. We identified several microcameras suitable for our needs, with the HiLetgo OV7670 Camera Module standing out.

5.1 Example 1

The HiLetgo OV7670 operates at 2.5–3.0 V and consumes a maximum of 60 mW when in use. Its voltage requirements can easily be met using a boost converter, as demonstrated in junior design projects, and its low power consumption ensures it won't strain the power supply. Additionally, the module communicates via I2C, a protocol we are experienced with, and the selected microcontroller architecture offers a convenient library for I2C communication. The camera is also affordably priced, with a unit cost of \$4.50 on Amazon or \$2.96 on AliExpress. Finally, its compact dimensions of 35 x 35 x 30 mm make it suitable for integration into our design without conflicting with the overall system footprint, which must remain compact enough to fit on a standard desk

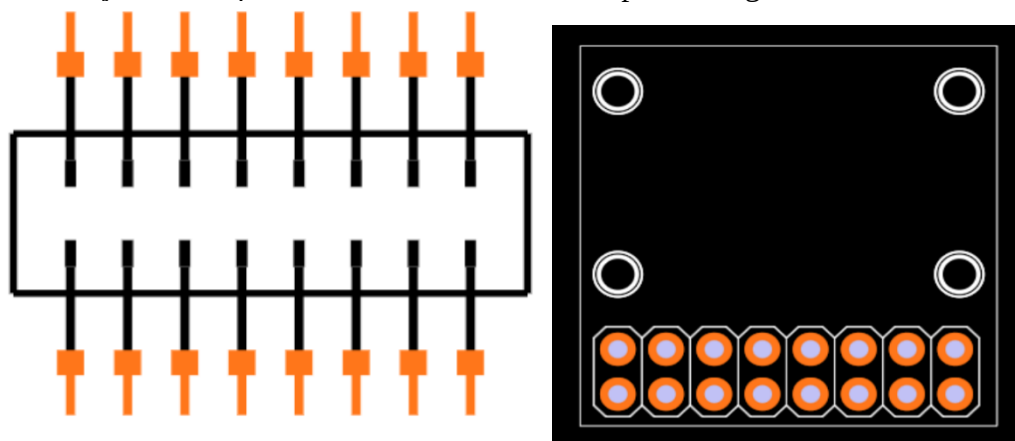


Figure 5-1: Symbol left and footprint right for the Hiletgo OV7670 Camera Module

However, the primary challenge of using computer vision lies in the significant computational power required for image processing at speeds necessary to make the final product viable. According to GeeksForGeeks, even a simple machine learning algorithm requires 16 GB of RAM for reasonable performance. Lightweight machine learning algorithms like YOLOv3 Tiny still require a minimum of 1 GB of RAM. By contrast, the microcontrollers under consideration for this project, such as the ATmega328P and MSP430, only offer 32–64 KB of RAM, which is far below the requirements for any meaningful image processing.

To address this limitation, we considered moving the image processing to an external server. Both microcontrollers support Wi-Fi expansion cards, enabling the microcontroller to capture an image and transmit it to an externally hosted site for processing. The processed result would then be sent back to the local machine for further action.

While this solution is technically feasible, it introduces several new challenges. The money sorter is designed to be stationary, placed in a bank or similar location where a consistent internet connection can be assumed. However, developing a remote image detection algorithm using the TensorFlow library and hosting it on an AWS server would add considerable complexity to the project. Combined with the mechanical aspects of handling and sorting money, the electrical challenges of balancing motors and sensors, and the embedded programming required for efficient machine operation, adding server programming would expand the scope of the project into a computer science-focused senior design project.

Moreover, an AWS server would introduce ongoing costs for hosting and maintenance, which would strain the budget for both development and production. Additionally, while our team consists of three computer engineering majors with expertise in computer architecture, embedded systems, and hardware security, none of us have experience with server management or Python programming beyond what has been covered in class. These factors made the machine-learning approach to orientation detection infeasible for this project.

5.2 Example 2

User Question: “What stepper motor would you recommend for a machine requiring precise movement?”

AI Answer:

For a machine requiring precise movement, I'd recommend looking into a bipolar stepper motor with high step resolution, such as a NEMA 17 or NEMA 23 motor, depending on your machine's size and torque requirements. Here are some factors to consider:

Recommended Motors

1. NEMA 17 Stepper Motor
 - Good for lightweight, smaller machines like 3D printers or small CNC machines.
 - Typical step angle: 1.8° (200 steps/rev) or finer with microstepping.
 - Torque: Around 40–60 oz-in (depending on model).
2. NEMA 23 Stepper Motor
 - Suitable for medium to heavy-duty applications, such as milling machines or larger CNC routers.
 - Typical step angle: 1.8° or finer.
 - Torque: Around 120–280 oz-in (depending on model).
3. High-Torque Versions
 - If your machine requires high torque at low speeds, look for high-torque versions of these motors, often with longer bodies or higher current ratings.

Considerations

- **Driver Compatibility:** Pair the motor with a suitable stepper motor driver that supports microstepping for increased precision (e.g., DRV8825, TMC2209, or DM556 for larger motors).
 - **Voltage and Current Ratings:** Ensure your power supply and driver can handle the motor's requirements.
 - **Precision Needs:** Use a motor with a step angle of 0.9° (400 steps/rev) if greater accuracy is needed.
 - **Load Requirements:** Match the motor torque to the load to avoid stalling or overheating.
- Would you like help calculating torque requirements or advice on controllers for these motors?
-

In this case, ChatGPT recommendations would be a good starting place as no other information about the project had been given. For any updated questions, ChatGPT is now running from a database from June 2024, and can also live search the internet during the processing of a request. While ChatGPT has vastly improved in recent years, it still has some issues that can hinder.

5.3 Example 3

When evaluating the required specifications, ChatGPT was consulted to assist in determining an appropriate operating temperature range. Given the complexity of a required operating temperature range of a device composed of multiple integrated components, ChatGPT served as a valuable starting point in identifying a suitable range that aligns with typical indoor commercial environments.

User Question:

“What would be a suitable operating temperature range for a portable, tabletop money-sorting device that aligns US bills into the same orientation, draws a maximum of 60W of power, and is intended for use in locations such as banks?”

AI Answer:

“For a portable, tabletop money-sorting device used in indoor commercial environments like banks, a suitable operating temperature range would typically be:

Recommended	Operating	Temperature	Range:
0°C to 40°C (32°F to 104°F)			
• Why this range?			
1. Indoor Use Assumption: Since it's for use in locations like banks, the device will likely be in climate-controlled environments. 2. Electronics Safety: Most consumer and office-grade electronics are designed to operate safely in this temperature range. 3. Mechanical Components: Sorting mechanisms and motors may be sensitive to temperature extremes; operating within this range ensures consistent performance and reduces wear. 4. Plastic & Rubber Components: Materials like belts, rollers, or guides could deform or become brittle outside this range.			

- Optional Additions:
 - Humidity Range: 20% to 80% RH (non-condensing) is also common.
 - Storage Temperature: -20°C to 60°C (-4°F to 140°F), if you plan to include specs for shipping or long-term storage.”
-

From this answer, the importance of having a low maximum temperature in the operating range is emphasized, due to the potential for material degradation. ChatGPT notes that the device will likely be used in a temperature-controlled environment. However, it is unable to provide specific information on electrical component temperature limits, as no detailed component specifications were provided. As a result, it assumes the use of “consumer and office-grade electronics”—an assumption that is partially accurate, but does not fully represent the intended design.

5.4 Example 4

One of the most valuable applications of ChatGPT is its ability to summarize website content in a clear and readable format. When evaluating AC power supply adapters, it is essential to extract key specifications from product pages. However, websites like Amazon often present technical information in a disorganized manner, with relevant details scattered throughout the page. In such cases, ChatGPT can be effectively utilized by uploading the webpage, allowing it to extract and consolidate critical information into a concise and accessible summary.

User Question:

“Could you provide a summary of the specifications for this AC power supply adapter, including, but not limited to, its configuration, electrical characteristics, and physical dimensions?
https://www.amazon.com/HitLights-Adapter-Lighting-Transformers-Supply/dp/B00HENQAMS?source=ps-sl-shoppingads-lpcontext&ref_=fplfs&smid=ATVPDKIKX0DER&gQT=1&th=1”

AI Answer:

“The HitLights 12V 5A Power Supply Adapter is designed to convert standard 120V AC household current into 12V DC output, suitable for powering various low-voltage devices, particularly LED lighting systems. Below is a summary of its key specifications:

Electrical Characteristics:

- **Input Voltage:** 120V AC
- **Output Voltage:** 12V DC
- **Output Current:** 5 Amps
- **Power Output:** 60 Watts
- **Frequency:** 60 Hz

Configuration:

- **Mounting Type:** Plug-in adapter
- **Power Source:** AC

Physical Dimensions:

- **Item Weight:** 0.75 pounds

Certifications:

- **Safety Compliance:** UL-Listed, ensuring adherence to recognized safety standards

This adapter is commonly used for LED lighting applications and other low-voltage devices requiring a stable 12V DC power source.”

This summary, along with those for other evaluated components, significantly supported the component evaluation and selection process. For this specific power supply, ChatGPT highlighted its UL safety certification—a valuable feature that had not yet been considered. Additionally, the summary provided all the necessary specifications and noted that power supplies of this type are commonly used in applications such as LED lighting. This insight further informed our understanding of the product and its typical use cases.

5.5 Example 5

Shifting focus from the technical aspects of our project to its market potential, ChatGPT proved to be a valuable tool in assessing the hypothetical demand for a product like ours. It can extract and concisely present objective data available online. In this instance, the following exchange was interpreted to evaluate the potential benefits our product could offer to an average US bank.

User Question:

“In the United States in 2025, how much time does the average bank teller spend each day manually sorting currency so that all bills are oriented the same way before storing them?”

AI Response:

“Could you please clarify if you're looking for data across all U.S. banks or specific types (e.g., national vs. regional, or retail vs. commercial)? Also, are you interested in an industry-wide average or estimates based on anecdotal or observational studies? Let me know if you're only concerned with cash handling (not including coin sorting, deposits, etc.).”

User Response:

“All banks, industry-wide averages, and cash handling only.”

AI Answer:

Got it — I’ll look into industry-wide averages for how much time U.S. bank tellers spend per day manually sorting paper currency to ensure all bills are oriented the same way before storing them, focusing strictly on cash handling. I’ll update you once I have the findings.

Time Spent by U.S. Bank Tellers Facing and Sorting Currency

Overview: U.S. bank tellers spend a non-trivial portion of each workday on manual cash handling tasks – including counting paper bills and **“facing” them (aligning all notes in the same orientation)** – before securing the cash. While hard data is scarce, industry estimates and case studies shed light on how much time this consumes on average:

- **Per-Transaction Estimates:** Industry analyses suggest **each cash transaction can add significant handling time**. A Sesami branch efficiency study notes that *“during a standard retail cash transaction, tellers spend at least two minutes counting, sorting or handling bills”*

([Cash recyclers transform customer service and help increase profits | Sesami](#)). Similarly, a bank technology blog compared manual vs. automated cash counting and found a teller typically takes about **45–60 seconds** to count out cash for a single customer, versus ~8 seconds with a machine; over ~60 cash transactions a day this **adds up to roughly one hour daily** with the teller’s head down handling cash ([5 Things to know about Teller Cash Recyclers \(Part 1 of 4\)](#)). Another source observes that the **cash-handling portion alone is often 20–45 seconds per transaction** even for routine counts ([Controlling cash operations in the branch environment | Sesami](#)) – time that can quickly accumulate across dozens of transactions.

- **Daily Averages:** Aggregating those seconds per transaction, **estimates for daily time spent manually sorting and aligning currency range from a few minutes up to an hour or more.** In a moderate-volume branch (e.g. ~30 cash transactions), a teller might spend on the order of **15–30 minutes per day** just on counting and facing paper money. In busier settings (50–60+ cash transactions), this can approach **60+ minutes per day** devoted strictly to handling and orienting bills ([5 Things to know about Teller Cash Recyclers \(Part 1 of 4\)](#)). These estimates align with vendor reports that a large share of teller labor is tied up in manual cash duties. For example, Fiserv notes that automating cash handling can **cut counting time by ~80%**, freeing tellers for customer service ([Eight Ways Teller Cash Recyclers Can Transform Branches | Fiserv](#)) ([Eight Ways Teller Cash Recyclers Can Transform Branches | Fiserv](#)). In fact, one case study reported that introducing cash recyclers saved “**over 3 hours of tellers’ time**” per day (in a branch that previously required extensive manual counting, dual controls, and bill facing) ([Controlling cash operations in the branch environment | Sesami](#)). Another banking automation provider even cited some clients saving “**as many as four hours per teller a day**” after eliminating manual cash sorting tasks ([Cash recyclers transform customer service and help increase profits | Sesami](#)) – implying that in certain high-cash environments, tellers had been spending nearly half their workday on counting, **straightening, and orienting currency.**
- **Qualitative Insights:** Even without exact stop-watch data, **banking practitioners acknowledge that bill-facing is a time-consuming chore.** In an industry forum, one veteran banker lamented that Federal Reserve cash shipments now arrive with bills “*turned every which way,*” forcing tellers to “**go through every single bundle and face them correctly... which is very time consuming**” ([Currency from Fed | For Bankers. From Bankers](#)). Tellers are trained to keep currency **face-up and neatly aligned** at all times for accuracy and professionalism, so they often spend spare moments during or between transactions flipping notes to the same orientation. While this “**facing**” practice makes subsequent counts easier and looks more orderly for customers, it does eat into productivity. Bank operations experts note that **every minute spent handling and organizing cash is a minute not spent on customers or other duties** ([Manual Cash Handling Horrors and How to Conquer Them](#)) ([Manual Cash Handling Horrors and How to Conquer Them](#)). This has prompted many U.S. banks to invest in currency counters/sorters that automatically orient bills, aiming to reduce the manual workload.

Bottom Line: *By 2025, available evidence indicates that the average U.S. bank teller may spend on the order of **dozens of minutes per day** (ranging roughly from 15 minutes in slower settings up*

to an hour or more in cash-heavy branches) **manually sorting and facing paper currency**. Exact time varies with branch cash volume and individual bank policy, but both quantitative studies and industry anecdotes affirm that **orienting bills is a significant daily task for tellers** ([5 Things to know about Teller Cash Recyclers \(Part 1 of 4\)](#)) ([Currency from Fed | For Bankers. From Bankers](#)). This time burden is widely recognized in the banking industry, which is why modern cash automation tools are touted for reclaiming those hours and improving teller efficiency ([Cash recyclers transform customer service and help increase profits | Sesami](#)) ([Cash recyclers transform customer service and help increase profits | Sesami](#)).

Sources:

- Sesami (banking automation firm) – *Branch operations blog*, noting **2 minutes** of manual cash handling per typical transaction ([Cash recyclers transform customer service and help increase profits | Sesami](#)).
- ValueTec Financial Equipment – *Teller efficiency article*, calculating **~1 hour/day** spent counting/orienting cash for ~60 transactions ([5 Things to know about Teller Cash Recyclers \(Part 1 of 4\)](#)).
- BankersOnline forum – Discussion where a banker calls manual bill-facing “**very time consuming**” for tellers ([Currency from Fed | For Bankers. From Bankers](#)).
- Sesami case study – Reporting **3–4 hours** of daily teller labor saved by automating cash sorting/facing tasks ([Controlling cash operations in the branch environment | Sesami](#)) ([Cash recyclers transform customer service and help increase profits | Sesami](#)).
- Cornerstone Credit Union League – *Teller training manual*, emphasizing all currency must be **face-up and same direction** as a standard procedure.”

For this ChatGPT response, we utilized the “Deep Research” feature—a new capability released on February 3, 2025. This feature allows ChatGPT to anonymously search the web for up-to-date information based on a user-specified topic and deliver a professionally written summary. Unlike the standard ChatGPT model, which relies on pre-trained data, Deep Research pulls current information directly from online sources and includes citations. It also conducts a more thorough analysis than the standard model.

The primary trade-off is that Deep Research takes longer to generate a response compared to standard queries. However, it is especially valuable when specific studies, statistics, or current data are needed, making it an ideal fit for our use case. In this instance, Deep Research spent six minutes analyzing 20 sources to generate the provided insights.

According to the information gathered, bank tellers in the U.S. spend a significant amount of time performing a process known as “facing”—the act of aligning all currency notes in the same direction. Sesami reports that an average of two minutes of cash handling time is required per bank transaction, while ValueTec Financial Equipment estimates that tellers spend approximately one

hour per day on cash handling tasks. Based on these findings, it can be concluded that a product like ours addresses a relevant and time-consuming challenge in the banking sector, and there would likely be sufficient market demand to support its adoption.

5.6 Example 6

Another valuable feature of AI platforms—such as Google Gemini in this case—is their ability to generate images based on user-provided prompts. Here, I provided Gemini with a rough description of our device and asked it to render a visual representation of what the final product might look like.

User Question:

“Please create an image of a device designed to align U.S. bills using a retractable vertical rolling track that flips the bills, followed by a rotating plate mechanism that orients them uniformly. The bills begin at an entry box in a stack, moving one at a time along a track to an exit box.”

AI Answer:

“Sure, here is an image of a device designed to align U.S. bills using a retractable vertical rolling track that flips the bills, followed by a rotating plate mechanism that orients them uniformly. The bills begin at an entry box in a stack, moving one at a time along a track to an exit box.”



Figure 5-2: *AI Render of Money Sorting Machine*

While this image isn't an accurate representation of our intended final design, it served as a helpful starting point in the machine's design process.

Chapter 6 – Hardware Design

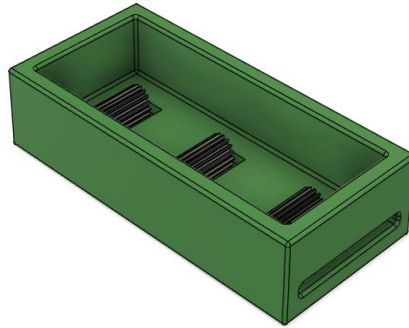


Figure 6-1: Entry Box

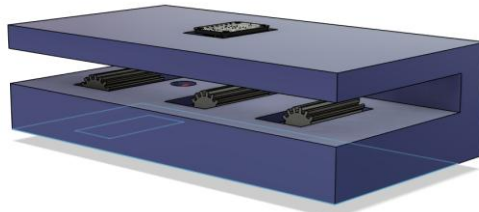


Figure 6-2: Color Detector/Bill Rejector



Figure 6-3: Flipper Mechanism

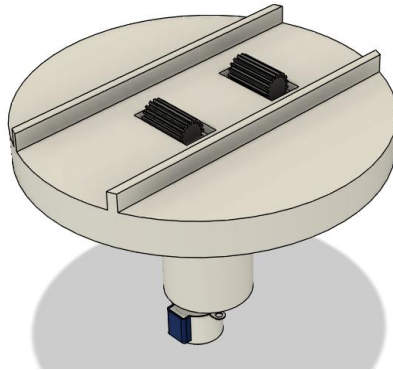


Figure 6-4: Rotating Mechanism

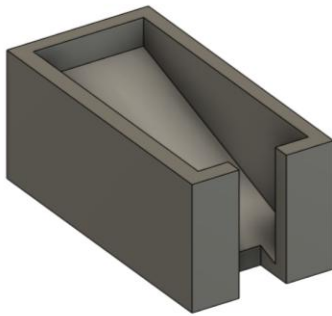


Figure 6-5: Output Collection Box

Chapter 7 – Software Design

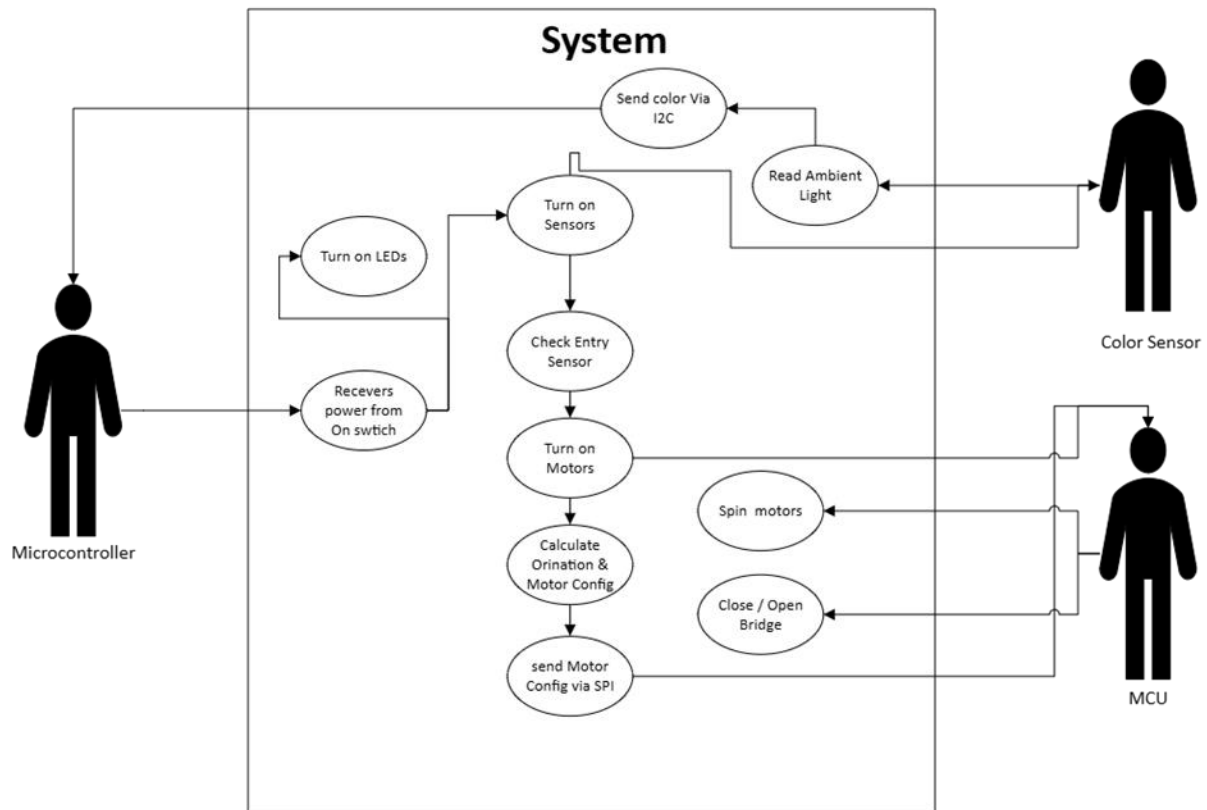


Figure 7-1: User Diagram

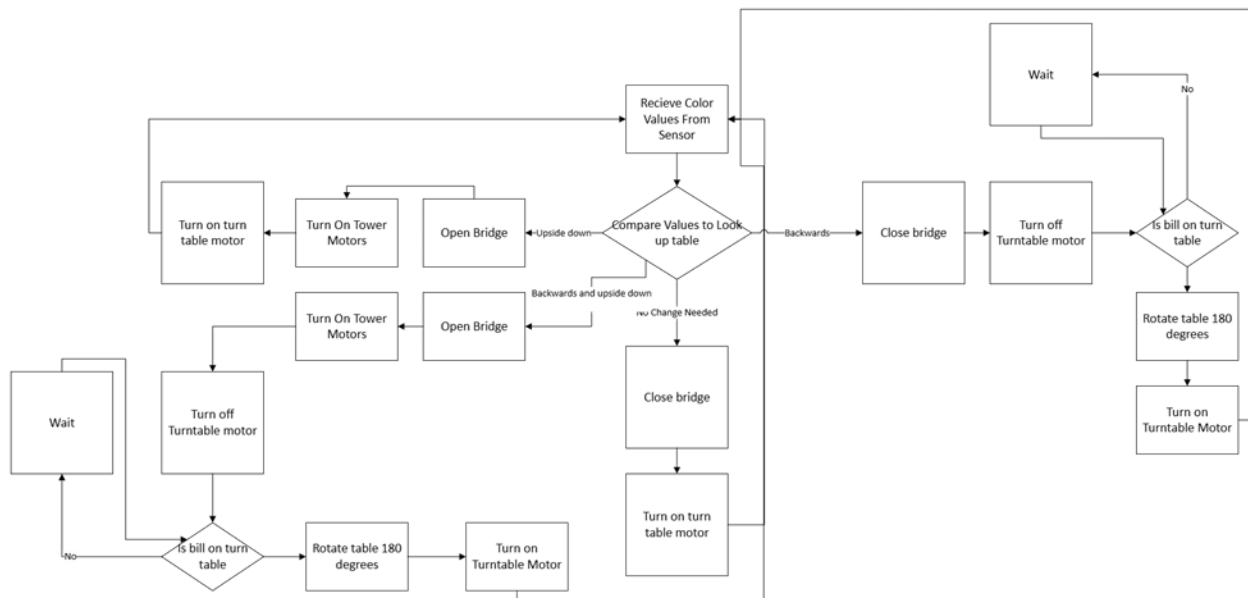


Figure 7-2: Motor Control Flow Chart

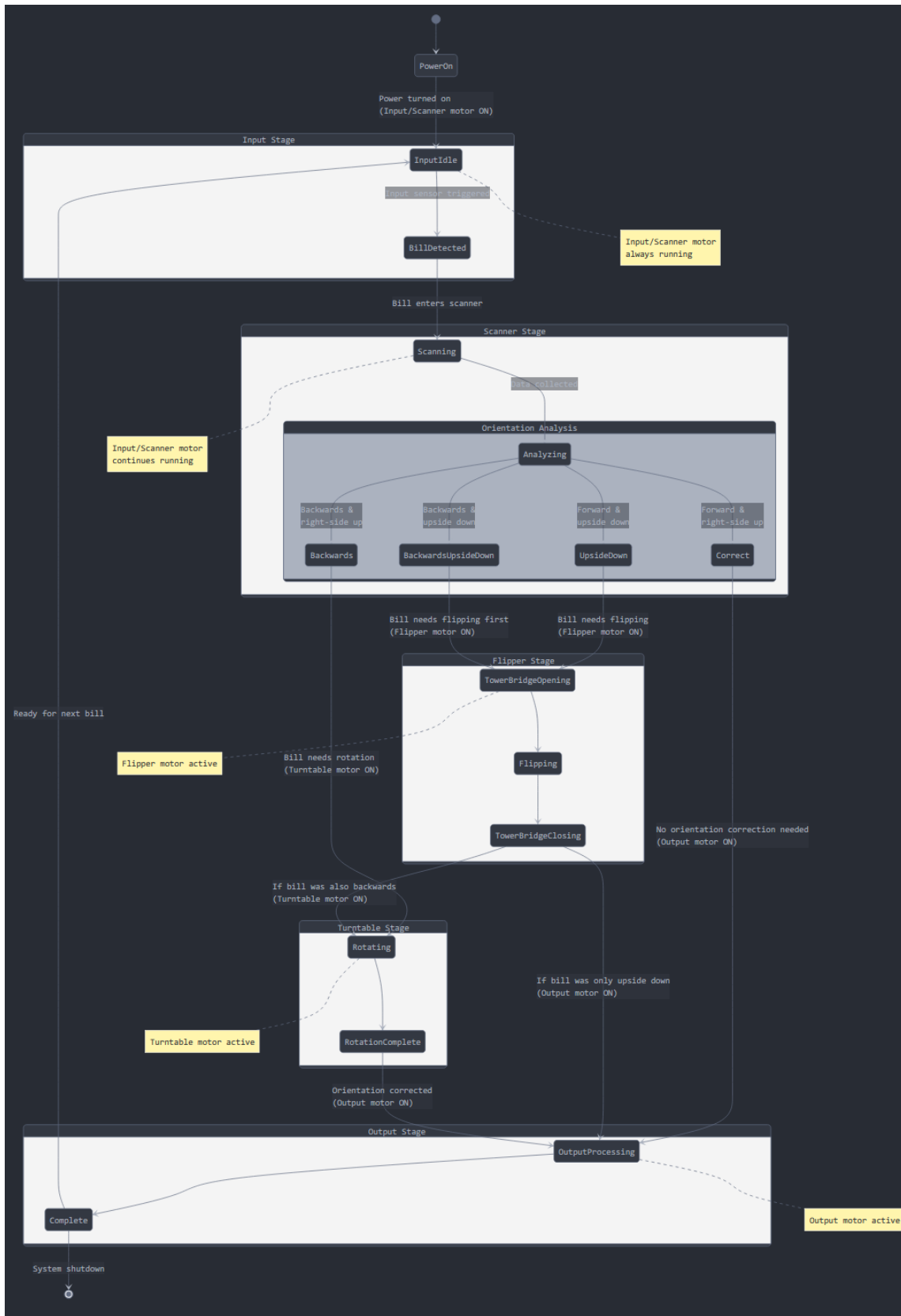


Figure 7-3: State Diagram

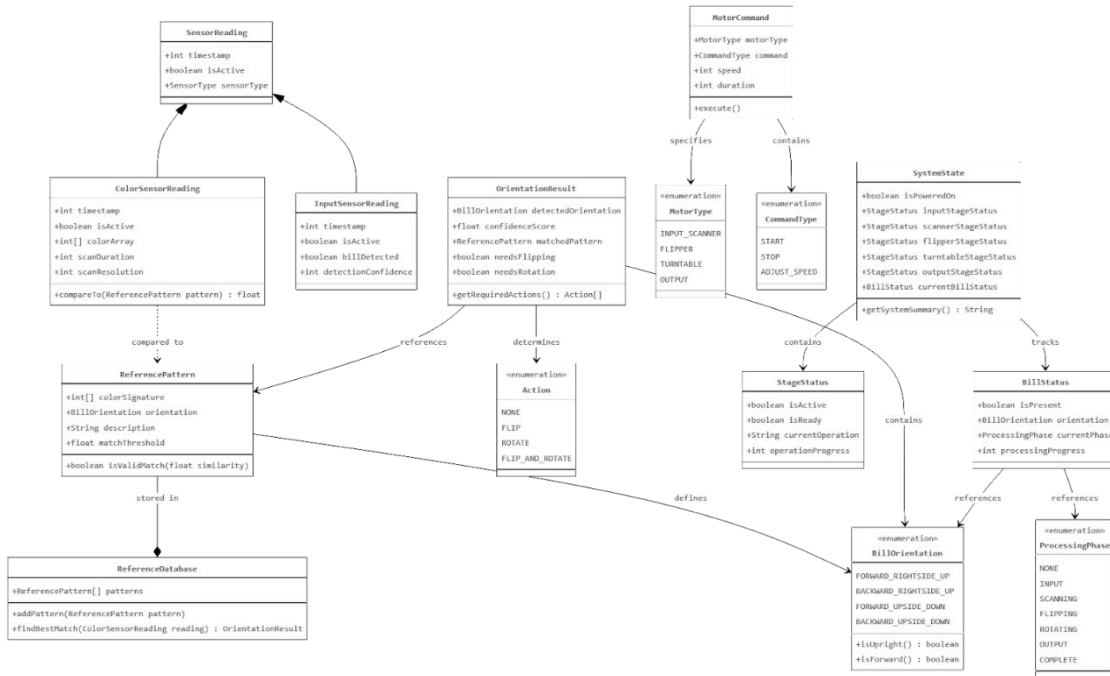


Figure 7-4: Data Structure Diagram

Chapter 10 – Administrative Content

10.1 Project Milestones

The provided milestones are tentative and serve as a general reference guideline. Weekly meetings are scheduled, including one main team meeting and individual breakout meetings for each task group throughout the week. This structure ensures that each team member collaborates with different parts of the team up to three times per week, promoting effective communication and coordination.

Table 10-1 Project Milestones

Task	Start Date	End Date	Duration (Days)	Duration (Weeks)
Project Selection	1/9/2025	1/12/2025	3	3/7
Project Scope	1/12/2025	1/17/2025	5	5/7
Research	1/12/2025	1/21/2025	9	1 2/7
Initial D&C Document	1/12/2025	1/24/2025	12	1 5/7
Final D&C Document	1/24/2025	2/7/2025	14	2
30-Page Milestone	1/12/2025	2/7/2025	26	3 5/7
Individual System Designs	1/12/2025	2/7/2025	26	3 5/7
60-Page Milestone	2/7/2025	3/1/2025	22	3 1/7
Individual System Testing	2/7/2025	3/7/2025	28	4
90-Page Milestone	3/1/2025	3/23/2025	20	2 6/7
PCB Design/Ordering	4/1/2025	4/28/2025	28	4
120-Page Milestone	3/23/2025	4/11/2025	21	3
Prototyping	4/6/2025	4/22/2025	16	2 2/7
Final Report	4/11/2025	4/22/2025	11	1 4/7

10.2 Budget

This project is entirely student-funded, with a self-imposed budget cap of \$450 to ensure costs remain manageable for each team member. This budget constraint encourages careful planning and efficient resource allocation, pushing the team to focus on balancing cost-effectiveness with quality and functionality.

Critical components such as the microcontroller and motors have been assigned a larger portion of the budget, as they are essential to the core operation of the project. These components are key to achieving the desired performance, so allocating sufficient funds to them ensures the overall reliability and success of the system. Meanwhile, less critical items, such as auxiliary components and connectors, have been sourced with cost minimization in mind, opting for alternatives that maintain acceptable quality without exceeding the budget.

The team has also prioritized reusability and resource-sharing, leveraging 3D printers and tools available on campus to reduce expenses for custom parts and prototypes. This strategy not only keeps costs down but also allows for iterative development without significant financial impact.

By carefully managing expenditures and focusing on high-impact items, the team ensures the project stays within the set financial limits while delivering a functional and reliable product.

Table 10-2 Budget Allocation for Project

Component	Budget
PCBs and Electronics	\$200
Materials	\$100
PSU and Motors	\$150
Total	\$450

Compared to the Bill of Materials outlined below, the project is currently under budget. This strategic allocation not only allows for efficient resource utilization but also provides flexibility for potential fluctuations or unexpected challenges that may arise during the development process. A slightly higher budget acts as a safety net, ensuring that the team can address unforeseen issues without compromising the quality or progress of the project. higher budget this allows for fluctuations and unexpected issues.

10.3 Bill of Materials

Table 10-3 Itemized Bill of Materials

Component	Name	Quantity	Cost
Power Supply	LX60-120500-D1	1	\$19.99
Power Distribution Block	QBLOK7001	10	\$19.47
Motors	G12-N20 Geared Mini DC Motor	10	\$15.00
MCU	DRV8912-Q1	1	\$5.33
Sensors	H2010 & LM393	5	\$1.60
Plastic Material	ABS	2	\$50.00
Acrylic Material	Cast Acrylic (GS)	10ft	\$18.00
Wood Material	Plywood	4ft	\$12.00
Microcontroller	Arduino Mega 2560	1	\$24.79
Drive Belt Material	Polyurethane Tubing	6ft	\$15.00
Printer Rollers	Ricoh AF03-1081	30	\$40.24
Regulator Fabrication		20	\$1.50
PCB Fabrication		10	\$7.00
Arduino Testing Board		1	\$20.00
Wires		120	\$0.02
Miscellaneous Items	Resistors, Inductors, Jumpers, Etc		~\$20.00
Total Cost			\$249.94

10.4 Work Distribution

The following outlines the distribution of work among team members, with assigned responsibilities for each area. However, during the prototyping phase, team members may need to

collaborate across different areas or shift roles, with secondary responsibilities potentially becoming primary. This flexibility is essential to leverage the unique expertise of each team member, ensuring greater efficiency and effectiveness throughout the project.

Table 10-4 *Distribution of Project Workload*

Project Manager: Emily Gensch		
Electrical		Responsibilities
Primary	Benjamin Harris	PCB Design
		PSU Design and Implementation
Secondary	Nicholas Heikes	PDB Design and Implementation
		Motor Implementation
Mechanical		Responsibilities
Primary	Henry Abshire	3D Design/Modeling
		Schematic Design
Secondary	Emily Gensch	Administrative Tasks
		Motor Implementation
Coding		Responsibilities
Primary	Nicholas Heikes	Sensor Selection and Implementation
		Software Design and Implementation
Secondary	Henry Abshire	Website Design and Management
		Motor Controls
Integration		Responsibilities
Primary	Emily Gensch	Part Testing and Integration
		Testing Model/Redesign
Secondary	Benjamin Harris	Documentation Editing
		Electrical Integrations/Modifications

Appendix A– References

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Appendix B – Copyright Permissions

[1] Figure: 3-2 - Brushless DC Motor

**John doe**
April 2, 2025 at 2:55 PM

My name is Henry Abshire, and I am a student at the University of Central Florida. My team and I are currently working on a project for our senior design project.

My team and I were hoping to obtain permission to reproduce figure 3 the schematic diagram for a brushless dc motor in our project documentation. We appreciate your help!

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[2] Figure: 3-3 - How Laser Cutters Work

* Contact

Tirdzniecibas vaditajs Latvija

* First name

Henry

* Last name

Abshire

* Email

he248516@ucf.edu

* Post Code

2164

* Your message

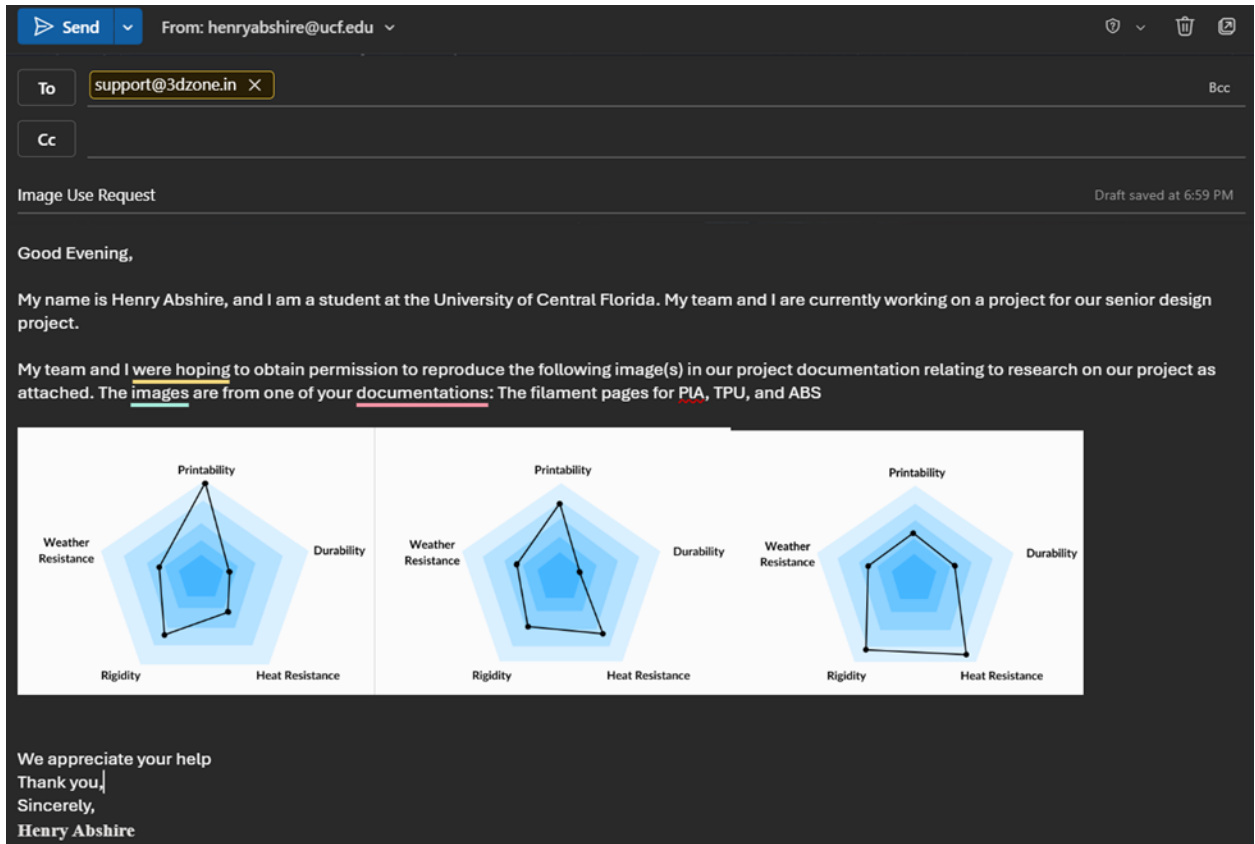
My name is Henry Abshire, and I am a student at the University of Central Florida. My team and I are currently working on a project for our senior design project.

My team and I were hoping to obtain permission to reproduce the following image(s) in our project documentation relating to research on our project as attached. The images are from one of your documentations: https://esab.com/lv/eur_en/esab-university/blogs/how-does-laser-cutting-work/

specifically, we would like permission to use the second image on the page: How Does Laser Cutting Work

We appreciate your help
Henry Abshire

[3] Figure: 3-12, 3-13, 3-14 - 3D printer filament charts



Appendix E – ChatGPT Prompts and Outcomes

[1] “ChatGPT - Precise Stepper Motor Selection.” ChatGPT, 2025, chatgpt.com/share/67e0c301-f93c-8009-86a5-4cc9ea492497. Accessed 24 Mar. 2025.

Question: “What stepper motor would you recommend for a machine requiring precise movement?”

Answer:

For a machine requiring precise movement, I'd recommend looking into a bipolar stepper motor with high step resolution, such as a NEMA 17 or NEMA 23 motor, depending on your machine's size and torque requirements. Here are some factors to consider:

Chapter 11 Recommended Motors

4. NEMA 17 Stepper Motor
 - Good for lightweight, smaller machines like 3D printers or small CNC machines.
 - Typical step angle: 1.8° (200 steps/rev) or finer with microstepping.
 - Torque: Around 40–60 oz-in (depending on model).
5. NEMA 23 Stepper Motor
 - Suitable for medium to heavy-duty applications, such as milling machines or larger CNC routers.
 - Typical step angle: 1.8° or finer.
 - Torque: Around 120–280 oz-in (depending on model).
6. High-Torque Versions
 - If your machine requires high torque at low speeds, look for high-torque versions of these motors, often with longer bodies or higher current ratings.

Chapter 12 Considerations

- Driver Compatibility: Pair the motor with a suitable stepper motor driver that supports microstepping for increased precision (e.g., DRV8825, TMC2209, or DM556 for larger motors).
- Voltage and Current Ratings: Ensure your power supply and driver can handle the motor's requirements.
- Precision Needs: Use a motor with a step angle of 0.9° (400 steps/rev) if greater accuracy is needed.
- Load Requirements: Match the motor torque to the load to avoid stalling or overheating.

Would you like help calculating torque requirements or advice on controllers for these motors?

[2] “ChatGPT - Conversation Used for Examples 3, 4, and 5 in Chapter 5.” ChatGPT, 2025, <https://chatgpt.com/share/67ecb491-5c8c-800c-9eb9-65b5155b3032>. Accessed 1 Apr. 2025.
What would be a suitable operating temperature range for a portable, tabletop money-sorting device that aligns US bills into the same orientation, draws a maximum of 60W of power, and is intended for use in locations such as banks?

For a **portable, tabletop money-sorting device** used in **indoor commercial environments** like banks, a suitable **operating temperature range** would typically be:

✅ **Recommended Operating Temperature Range:**

0°C to 40°C (32°F to 104°F)

💡 **Why this range?**

Indoor Use Assumption: Since it's for use in locations like banks, the device will likely be in **climate-controlled environments**.

Electronics Safety: Most consumer and office-grade electronics are designed to operate safely in this temperature range.

Mechanical Components: Sorting mechanisms and motors may be sensitive to temperature extremes; operating within this range ensures **consistent performance** and reduces wear.

Plastic & Rubber Components: Materials like belts, rollers, or guides could deform or become brittle outside this range.

✅ **Optional Additions:**

Humidity Range: 20% to 80% RH (non-condensing) is also common.

Storage Temperature: -20°C to 60°C (-4°F to 140°F), if you plan to include specs for shipping or long-term storage.

Let me know if you want help drafting a tech spec sheet or user manual snippet for this! Could you provide a summary of the specifications for this AC power supply adapter, including, but not limited to, its configuration, electrical characteristics, and physical dimensions?

https://www.amazon.com/HitLights-Adapter-Lighting-Transformers-Supply/dp/B00HENQAMS?source=ps-sl-shoppingads-lpcontext&ref_=fplfs&smid=ATVPDKIKX0DER&gQT=1&th=1

The HitLights 12V 5A Power Supply Adapter is designed to convert standard 120V AC household current into 12V DC output, suitable for powering various low-voltage devices, particularly LED lighting systems. Below is a summary of its key specifications:

Electrical Characteristics:

- **Input Voltage:** 120V AC
- **Output Voltage:** 12V DC
- **Output Current:** 5 Amps
- **Power Output:** 60 Watts
- **Frequency:** 60 Hz

Configuration:

- **Mounting Type:** Plug-in adapter
- **Power Source:** AC
- **Physical Dimensions:**
- **Item Weight:** 0.75 pounds

Certifications:

- **Safety Compliance:** UL-Listed, ensuring adherence to recognized safety standards

This adapter is commonly used for LED lighting applications and other low-voltage devices requiring a stable 12V DC power source. citeturn0search0

In the United States in 2025, how much time does the average bank teller spend each day manually sorting currency so that all bills are oriented the same way before storing them?

Could you please clarify if you're looking for data across all U.S. banks or specific types (e.g., national vs. regional, or retail vs. commercial)? Also, are you interested in an industry-wide average or estimates based on anecdotal or observational studies? Let me know if you're only concerned with cash handling (not including coin sorting, deposits, etc.).

All banks, industry-wide averages, and cash handling only.

Got it — I'll look into industry-wide averages for how much time U.S. bank tellers spend per day manually sorting paper currency to ensure all bills are oriented the same way before storing them, focusing strictly on cash handling. I'll update you once I have the findings.

Time Spent by U.S. Bank Tellers Facing and Sorting Currency

Overview: U.S. bank tellers spend a non-trivial portion of each workday on manual cash handling tasks – including counting paper bills and **“facing” them (aligning all notes in the same orientation)** – before securing the cash. While hard data is scarce, industry estimates and case studies shed light on how much time this consumes on average:

- **Per-Transaction Estimates:** Industry analyses suggest **each cash transaction can add significant handling time**. A Sesami branch efficiency study notes that *“during a standard retail cash transaction, tellers spend at least two minutes counting, sorting or handling bills”* ([Cash recyclers transform customer service and help increase profits | Sesami](#)). Similarly, a bank technology blog compared manual vs. automated cash counting and found a teller typically takes about **45–60 seconds** to count out cash for a single customer, versus ~8 seconds with a machine; over ~60 cash transactions a day this **adds up to roughly one hour daily** with the teller's head down handling cash ([5 Things to know about Teller Cash Recyclers \(Part 1 of 4\)](#)). Another source observes that the **cash-handling portion alone is often 20–45 seconds per transaction** even for routine counts ([Controlling cash operations in the branch environment | Sesami](#)) – time that can quickly accumulate across dozens of

transactions.

- **Daily Averages:** Aggregating those seconds per transaction, **estimates for daily time spent manually sorting and aligning currency range from a few minutes up to an hour or more.** In a moderate-volume branch (e.g. ~30 cash transactions), a teller might spend on the order of **15–30 minutes per day** just on counting and facing paper money. In busier settings (50–60+ cash transactions), this can approach **60+ minutes per day** devoted strictly to handling and orienting bills ([5 Things to know about Teller Cash Recyclers \(Part 1 of 4\)](#)). These estimates align with vendor reports that a large share of teller labor is tied up in manual cash duties. For example, Fiserv notes that automating cash handling can **cut counting time by ~80%**, freeing tellers for customer service ([Eight Ways Teller Cash Recyclers Can Transform Branches | Fiserv](#)) ([Eight Ways Teller Cash Recyclers Can Transform Branches | Fiserv](#)). In fact, one case study reported that introducing cash recyclers saved “**over 3 hours of tellers’ time**” per day (in a branch that previously required extensive manual counting, dual controls, and bill facing) ([Controlling cash operations in the branch environment | Sesami](#)). Another banking automation provider even cited some clients saving “**as many as four hours per teller a day**” after eliminating manual cash sorting tasks ([Cash recyclers transform customer service and help increase profits | Sesami](#)) – implying that in certain high-cash environments, tellers had been spending nearly half their workday on counting, **straightening, and orienting currency.**
- **Qualitative Insights:** Even without exact stop-watch data, **banking practitioners acknowledge that bill-facing is a time-consuming chore.** In an industry forum, one veteran banker lamented that Federal Reserve cash shipments now arrive with bills “*turned every which way,*” forcing tellers to “**go through every single bundle and face them correctly... which is very time consuming**” ([Currency from Fed | For Bankers. From Bankers](#)). Tellers are trained to keep currency **face-up and neatly aligned** at all times for accuracy and professionalism, so they often spend spare moments during or between transactions flipping notes to the same orientation. While this “**facing**” practice makes subsequent counts easier and looks more orderly for customers, it does eat into productivity. Bank operations experts note that **every minute spent handling and organizing cash is a minute not spent on customers or other duties** ([Manual Cash Handling Horrors and How to Conquer Them](#)) ([Manual Cash Handling Horrors and How to Conquer Them](#)). This has prompted many U.S. banks to invest in currency counters/sorters that automatically orient bills, aiming to reduce the manual workload.

Bottom Line: *By 2025, available evidence indicates that the average U.S. bank teller may spend on the order of **dozens of minutes per day** (ranging roughly from 15 minutes in slower settings up to an hour or more in cash-heavy branches) **manually sorting and facing paper currency.** Exact time varies with branch cash volume and individual bank policy, but both quantitative studies and industry anecdotes affirm that **orienting bills is a significant daily***

task for tellers ([5 Things to know about Teller Cash Recyclers \(Part 1 of 4\)](#)) ([Currency from Fed | For Bankers. From Bankers](#)). This time burden is widely recognized in the banking industry, which is why modern cash automation tools are touted for reclaiming those hours and improving teller efficiency ([Cash recyclers transform customer service and help increase profits | Sesami](#)) ([Cash recyclers transform customer service and help increase profits | Sesami](#)).

Sources:

- Sesami (banking automation firm) – *Branch operations blog*, noting **2 minutes** of manual cash handling per typical transaction ([Cash recyclers transform customer service and help increase profits | Sesami](#)).
- ValueTec Financial Equipment – *Teller efficiency article*, calculating ~**1 hour/day** spent counting/orienting cash for ~60 transactions ([5 Things to know about Teller Cash Recyclers \(Part 1 of 4\)](#)).
- BankersOnline forum – Discussion where a banker calls manual bill-facing “**very time consuming**” for tellers ([Currency from Fed | For Bankers. From Bankers](#)).
- Sesami case study – Reporting **3–4 hours** of daily teller labor saved by automating cash sorting/facing tasks ([Controlling cash operations in the branch environment | Sesami](#)) ([Cash recyclers transform customer service and help increase profits | Sesami](#)).

Cornerstone Credit Union League – *Teller training manual*, emphasizing all currency must be **face-up and same direction** as a standard procedure.

[3] “Gemini - Conversation Used for Example 6 in Chapter 5.” Gemini, 2025, <https://g.co/gemini/share/5aa63a68518c>. Accessed 1 Apr. 2025.

Please Create image of a device designed to align U.S. bills using a retractable vertical rolling track that flips the bills, followed by a rotating plate mechanism that orients them uniformly. The bills begin at an entry box in a stack, moving one at a time along a track to an exit box.

Sure, here is an image of a device designed to align U.S. bills using a retractable vertical rolling track that flips the bills, followed by a rotating plate mechanism that orients them uniformly. The bills begin at an entry box in a stack, moving one at a time along a track to an exit box:



