UNIVERSITY OF SOUTHERN CALIFORNIA
DEPARTMENT OF AEROSPACE AND MECHANICAL ENGINEERING

AME 503: ADVANCED MECHANICAL DESIGN

Sheet Music Semi-Automated Scroller

FINAL PROJECT REPORT
Group 7

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12 May 2025

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I. EXECUTIVE SUMMARY

Background
Traditional sheet music racks pose challenges for musicians during live performances, including the need to manually turn pages, inability to see the music, and disruptive adjustments, especially for multi-page compositions. These challenges were acknowledged in an ethnography study and inspired the development of a semi-automated scrolling solution to enhance user experience.

Objectives
The main goal of this project was to address the challenges highlighted in the ethnography study by developing a semi-automated sheet music scroller. The product should enable hands-free playing, enhance visibility, make setting up more efficient, and accommodate long musical pieces. The report tells the story from customer needs through conceptualization, prototyping, and feasibility analysis on how our product came to be.

Summary of Work
An ethnography study helped identify user frustrations while playing longer musical pieces which set guidelines for customer needs and functional requirements of the new product. The team developed and compared conceptual designs for multiple variants before settling on the most practical variant as defined by belief scores. The chosen variant is a semi automated automatic sheet music scroller complete with a foot pedal for human controls and a stepper motor mechanism to actuate the scrolling. Complete with sensors and controls programmed to stop a sheet at its end and detect the presence of a sheet, this variant was selected for its balance between automation and user accessibility. Detailed CAD models, tolerance analyses, and feasibility calculations confirmed the viability of the design. A working prototype was built using COTS and 3D printed parts.

Impact
The resulting design successfully enables hands-free, precise page scrolling. Since the relevant music is always directly in front of the user, it improves sheet visibility and usability during performance. The automatic sheet scroller provides a feasible, low-power, cost-effective solution that can be scaled through injection molding and refined for consumer use.

Future Work Plan
Future iterations will focus on improving packaging, integrating cleaner wiring, and miniaturizing components for consumer readiness. Additional user testing, safety validations, and potential battery-powered options will also improve the product. Cost optimization and usability enhancements are also recommended for market viability, and since it consists of many commercial and injection-moldable plastic parts, it has the potential to be profitable in high production volumes.

II. ETHNOGRAPHY STUDY

Date of study: 1/19/2025

Location: Albert's residence

Description: Albert and his friends were casually hanging out and playing the keyboard. Observing that displaying and turning the sheet music on the sheet rack to one's liking was unnecessarily difficult, frustrating, and inconvenient, Albert decided to conduct an ethnography study to potentially improve the process.

Subject 1

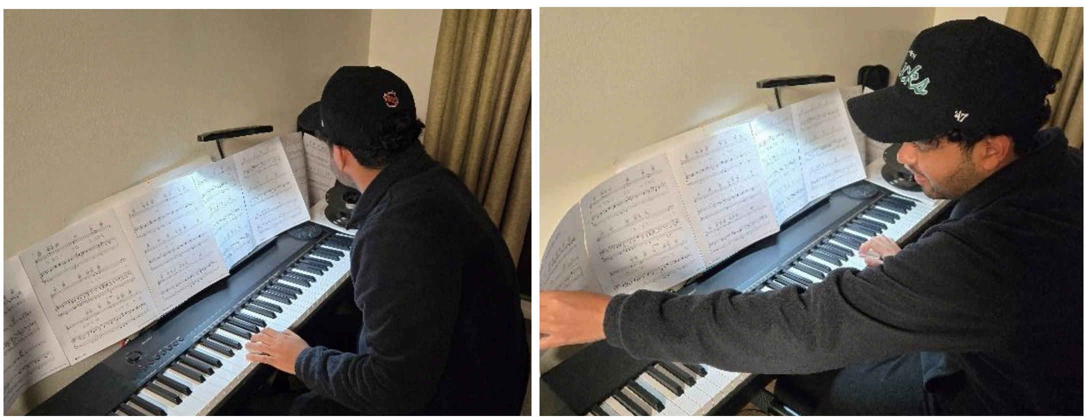


Figure 1: Shows subject 1 reaching for the first and last sheet of music

Subject 1 experienced difficulties and discomfort while trying to read the music on the far-end sheets. In order to read the pages, he had to pause his playing, lean over, and tilt the page towards him to see. Not only did this make it impossible to continuously play an entire piece of music end-to-end using the sheet music, but it also forced him to strain his vision and upper-body.

Subject 2

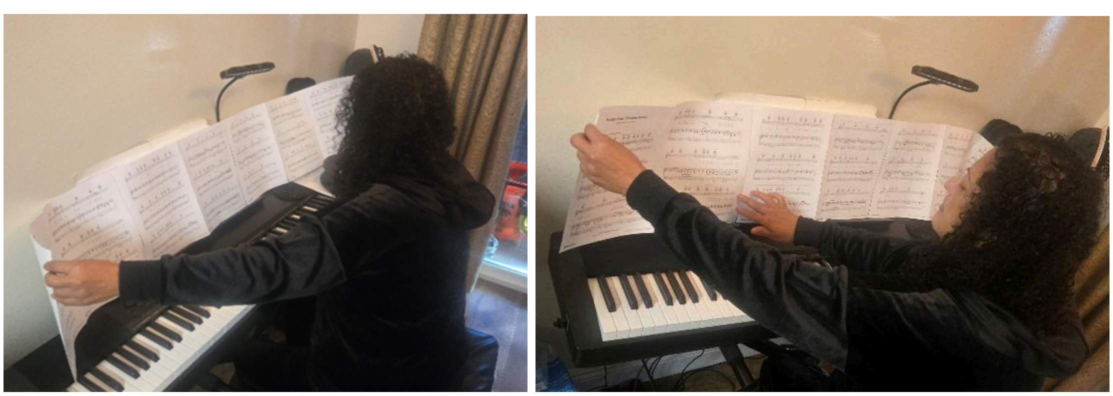


Figure 2: Shows subject 2 struggling to turn the pages of the sheet music and balance all of the relevant parts on the stand

Subject 2 displayed discomfort and frustration while aligning the sheet music on the rack to show the relevant parts of the piece. The second image in figure 2 depicts how difficult it is to then turn the page of one of the sheet packets once they're aligned. Sheets often must be folded to display the rest of the music, but when it comes time to turn the page on said sheet, it is very frustrating as you then have to realign the rest of the music.

Subject 3

Figure 3: Shows subject 3 struggling to see the small font while reading the music and attempting to turn a sheet with one hand while playing with the other

Subject 3 wears glasses and thus is not able to make out the small font of the sheet music. For a longer piece, this is very inconvenient because a smaller font means fitting more music into the sheets the user is reading from. With a larger font, the user would be able to see it better, but would have to turn more pages and make more adjustments in order to perform the piece. The third subject also displayed how inconvenient it is to play with one hand while turning the page with the other, which is a skill in itself.

III. CUSTOMER NEEDS

The ethnography study exposed faults in the feasibility of the standard sheet music rack which can be addressed by a new product. The following customer needs were identified to inspire functional requirements.

A. Hands-Free Operation

Subject 3 demonstrated how difficult it is to play with one hand while turning a page with the other, revealing a need for a system that eliminates the need for manual page turns during a performance.

B. Easy Page Visibility

Subject 1 had to lean over and tilt pages just to read music at the edges, indicating that users need a system that presents sheet music in a consistently visible and accessible way.

C. Large, Legible Display Options

Subject 3, who wears glasses, struggled with the small font on sheet music, showing a need for the ability to adjust display size or font for better readability.

D. Smooth Page Transition

All subjects experienced interruption when turning pages, underscoring the need for a smooth, uninterrupted page scrolling or turning function to maintain performance flow.

E. Accommodates Multi-Page Pieces

Subjects 1 and 2 had difficulty managing multiple pages at once, revealing a need to easily navigate long pieces without crowding or constant adjustment.

F. Minimal Setup and Interruption

Throughout the session, repositioning sheet music caused frustration and broke immersion, suggesting a need for a device that is simple to set up and does not interfere with the musical experience.

G. Portability and Compatibility

The casual, home-based nature of the session at Albert's residence implies a need for a device that is lightweight, compact, and usable across different formats and environments.

H. Fail-Safe / Manual Override

Given the frustration around misalignment and page flipping, users need the ability to override the system in case of error or unexpected behavior to regain control instantly.

I. Prevent/Mitigate Folding of Sheets

Subject 2 had to fold sheets to fit all the music on the stand, which then made turning pages even more frustrating due to misalignment and shifting. This highlights the need for a system that prevents the need to fold or manipulate pages to view the full piece.

With the above customer needs considered, it was decided that those most relevant to move forward with the design were:

1) Prevent/mitigate folding of sheets
2) Smooth/Automatic page transition
3) Portability and Compatibility
4) Minimal setup and interruption

By focusing on these specialized customer needs, the team ensures that the new product will make playing longer musical pieces easier and more practical, mitigate the need to turn, fold, or align pages for the musician, and offer a pleasant, cooperative experience.

IV. FUNCTIONAL MAP

From the customer needs established in the performed ethnography studies, functional needs for our product were developed. These functional needs were refined through three levels of decomposition and were organized via functional maps. This allowed for the visualization of signal, material, and energy flows between functions of the product which better informed our solution brainstorming in development of design parameter options for our morphology chart, improving the variety and cohesiveness of our developed design variant options.

Top Level

For the functional map, there were several externalities that interact with the system. The system energy was provided by potential energy of some of the system components used to hold the music sheet, electrical energy to power the product for motion and for some sensors, and external energy from the user to interact with the product to setup the sheet. The material in the system is the music sheet, which is loaded, then the product functions on the sheet, and then the sheet is unloaded. Signal in the system represents both electrical signals from some of the sensors used in the product to control its functionality as well as the "state" of the music sheet as it is scrolled by the product.

The overall design problem is the top level function of the product which is to scroll a music sheet, shown in the functional map below.

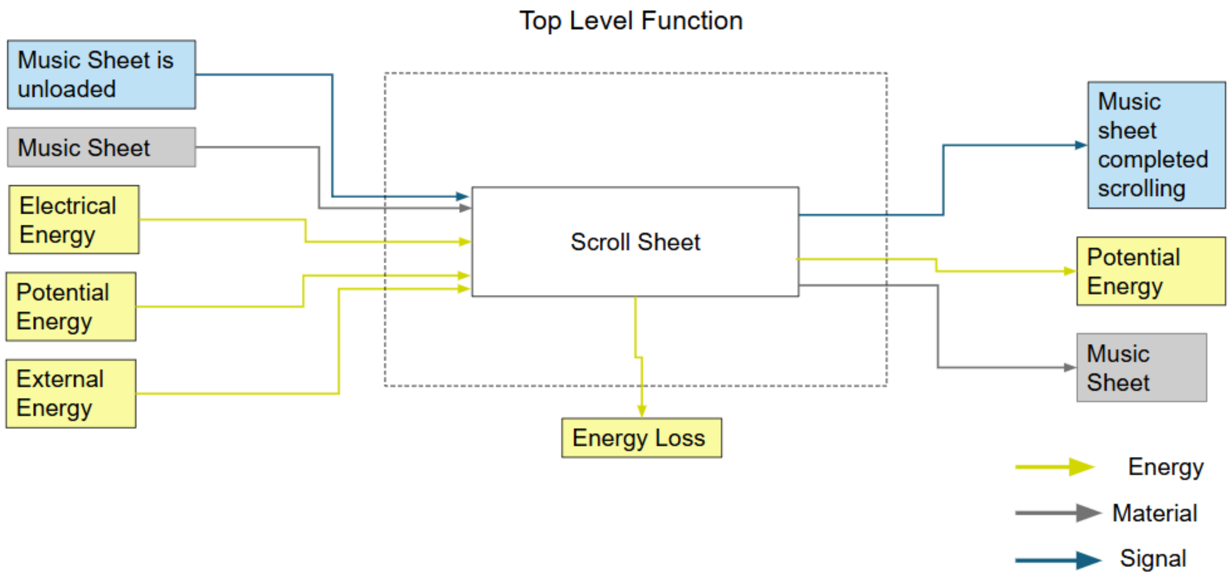


Figure 4: Top Level Functional Map

This function is then decomposed into 4 main system functions in the second level. These functions address key customer needs from the ethnography. Loading the sheet addresses user access and holding the sheet, scrolling the sheet addresses the need to keep the target section visible to the user, preventing folding maintains this visibility while also reducing distraction to the user, and scroll to completion completes the system functionality and allows the system to be set back to its initial, empty state. All of the external inputs and outputs to the system are maintained, though the connectivity to certain tasks starts to separate at this level.

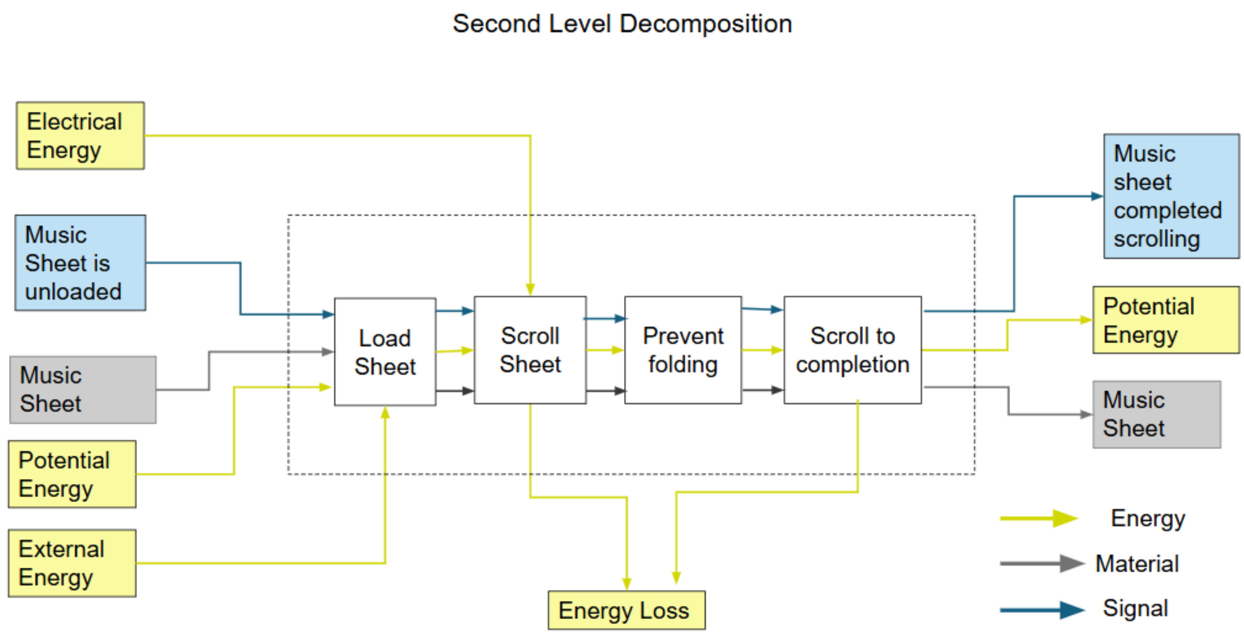


Figure 5: Second Level Functional Map

These main functions were then further broken down into 12 total functional needs for the system. These functions show a breakout of needs that can be addressed by individual design features in our variants. From the chart below, the most notable new functions are the breakout of functions related to holding and handling of the music sheet, as well as several functions for monitoring and controlling the sheet scrolling process. The 4 main functions from the second level map remain unchanged, supported by these new functions. Additionally, the system externalities remain unchanged, though it can be noted that several more functions now both take input energy and lose energy to the environment. With the several sources of energy loss the future design must take good account of the energy budget.

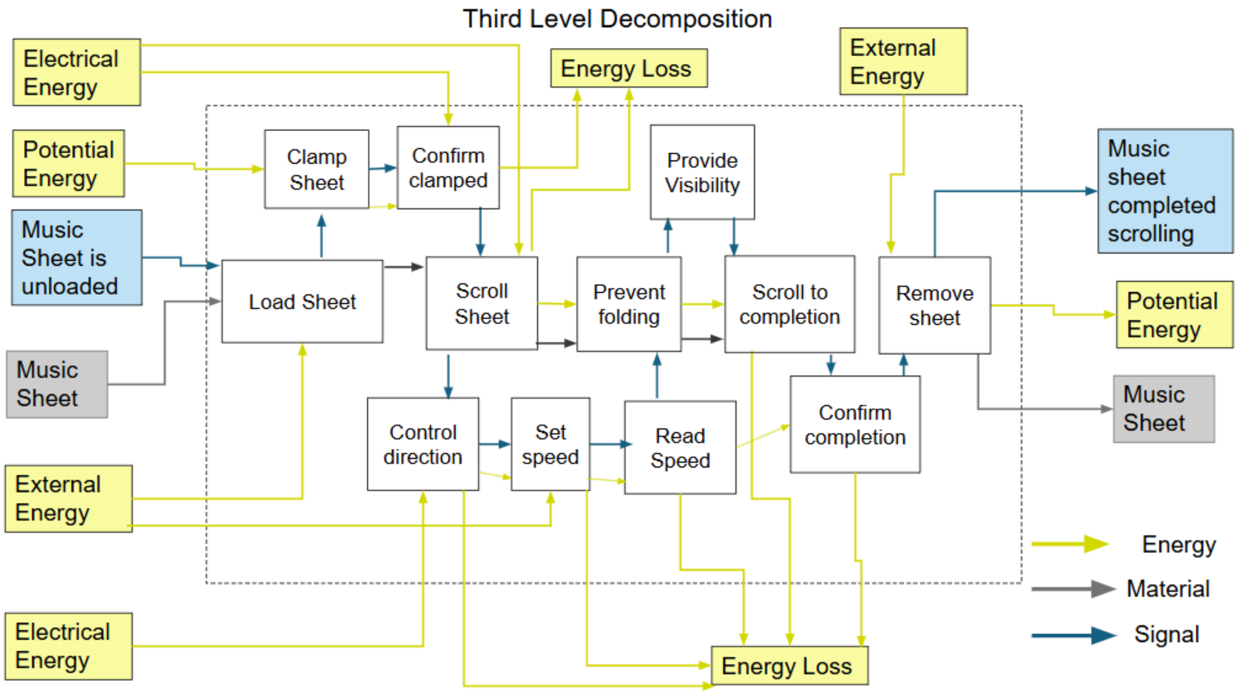


Figure 6: Third Level Functional Map

The functions (FN) were then put into the morphology chart in the next section to support the development of design parameters to meet the functional needs of the system.

V. CONCEPTUAL DESIGN

A. Morphology Chart

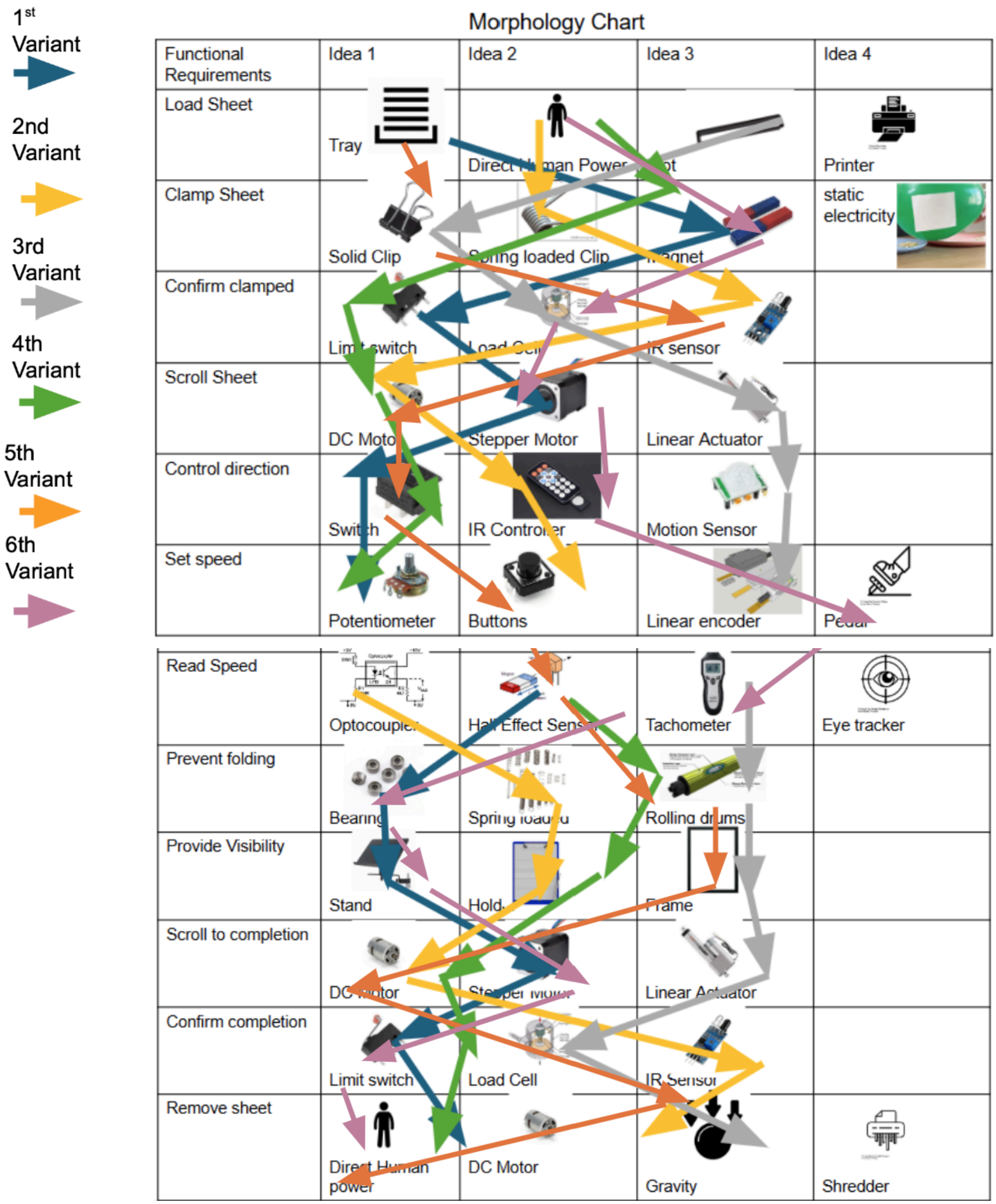
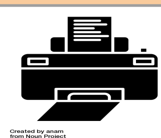
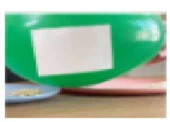
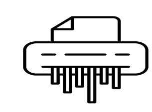


Figure 7. Morphology Chart

B. Alternate Design Parameters

The ideas explored in the early stages of brainstorming seemed interesting but weren't the right fit once we looked closer. The printer idea was not selected because printers are designed to move paper in short bursts and not in a continuous motion like our project needs. In addition, integrating a printer mechanism into the music scroller would require taking apart complicated hardware that could get messy. Plus, we were worried that the printer might run out of ink during mid performance of playing a song; therefore, it was not selected in any variants. Static electricity was considered but the team started to doubt its unpredictability of generating enough force to move the paper. Also, it's hard to control when or how it works. The eye tracker was another idea we dropped because it would have needed specialized hardware and software that was not available to us. Eye movements can be unsteady, and it will be difficult to make the system scroll only when one needs it to move. The last alternate design parameter that was not chosen was the shredder mechanism since it's designed to pull paper aggressively. This might tear or crumple music sheets not intended to be shredded. The morphology chart helped shape our ideas but at the end we stuck with options that were more practical and easier to build.

Table 1: Non-Chosen Options

Not Chosen Options	Discussion
Printer 	The printer was not selected because it required precise alignment that introduced more failure points than value such as taking too long to print while playing a song.
Static Electricity 	This option was dismissed because it's not a reliable and effective repeatable force for scrolling paper since it can be affected by environmental conditions like humidity.
Eye Tracker 	This option made the project innovative but it would require advanced image processing and it would be challenging to calibrate for scroll timing as well as eye positioning.
Shredder 	This option was not chosen because the music notes might need to be reused; therefore, making it incompatible with preserving music sheets during scrolling.

C. Variant Generation Discussion

Variant 1: Automated Feedback Based Control

Variant one was created with the goal of building a fully automated music scroller using components that provide consistent feedback and control. For every function, we selected sensors and actuators that could handle tasks without needing constant user input. For example, a limit switch was chosen to confirm when the sheet is clamped and when scrolling is complete. A stepper motor was chosen to move the music sheet. A stepper motor was chosen to move the music sheet because it offers precise control over movement, and a hall effect sensor was added to track the motor's speed. A potentiometer lets the user set the scrolling speed, while a switch handles the scroll direction. The tray helps with loading the music sheet and the magnet helps with securing the sheet in place. the bearings would help prevent folding as it moves. The DC motor removes the sheet after scrolling is complete. This setup ensures that each part of the system is either automated or provides measurable feedback making it well suited for a nearly hands-free operation.

- ❖ Focused on full automation and electronic feedback.
- ❖ Each function is backed by a sensor or actuator.
- ❖ Components were selected to ensure repeatability, accuracy, and monitoring.

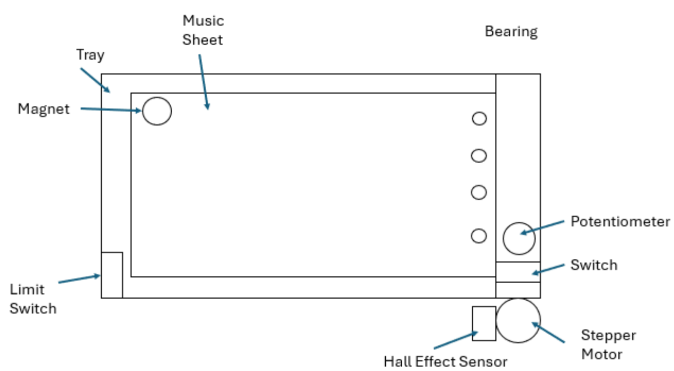


Figure 8: Drawing Variant 1

Functional Requirements	Variant 1: Ideas
Load Sheet	Tray
Clamp Sheet	Magnet
Confirm Clamped	Limit Switch
Scroll Sheet	Stepper Motor
Control Direction	Switch
Set Speed	Potentiometer
Read Speed	Hall Effect Sensor
Prevent Folding	Bearing
Provide Visibility	Stand
Scroll To Completion	Stepper Motor
Confirm Completion	Limit Switch
Remove Sheet	DC Motor

Figure 9: Variant 1 Ideas

Variant 1	Score
Knowledge	0.8
Confidence	0.7
Belief	0.62

Figure 10: Variant 1 Belief Scores

Variant 2: Low Cost Human Aided Hybrid

Variant two was designed with a focus on simplicity and low cost. It's more dependent on user interaction rather than full automation. The music sheet is loaded and removed manually by the user in order to remove mechanical complexity. A spring loaded clip helps secure the sheet in place, and an IR sensor is used to detect when the sheet is clamped or when scrolling is complete. Scrolling takes place by a DC motor, and the user controls the scroll direction using a IR Sensor remote controller. Speed can be adjusted through buttons, and an optocoupler provides basic feedback for speed reading. To keep the sheet from folding during movement, springs support the edges, and a simple holder helps maintain visibility of the music notes. Once scrolling is complete, the sheet is removed with the help of gravity. This helps avoid the need for a second motor. This design keeps costs low by reducing the number of components but it scored a very low belief score.However, it's a good backup solution where full automation isn't required.

- ❖ Based on low cost and simplicity by relying on human power for loading/removal.
- ❖ Offers limited automation by IR control and DC motors.
- ❖ Designed for cases where feedback is not critical, & user inputs are acceptable.

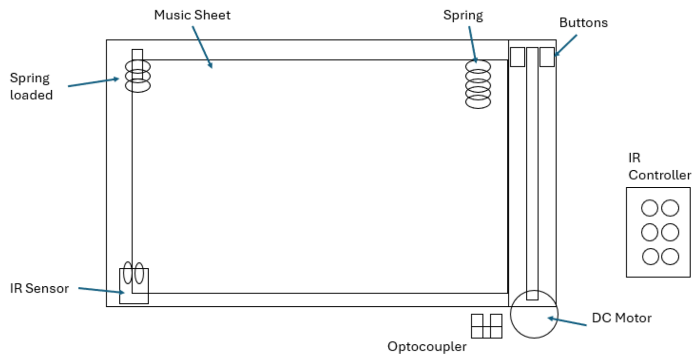


Figure 11: Variant 2 Drawing

Functional Requirements	**Variant 2: Ideas**
Load Sheet	Direct Human Power
Clamp Sheet	Spring Loaded Clip
Confirm Clamped	IR Sensor
Scroll Sheet	DC Motor
Control Direction	IR Controller
Set Speed	Buttons
Read Speed	Optocoupler
Prevent Folding	Spring Loaded
Provide Visibility	Holder
Scroll To Completion	DC Motor
Confirm Completion	IR Sensor
Remove Sheet	Gravity

Figure 12: Variant 2 Ideas

Variant 2	Score
Knowledge	0.6
Confidence	0.5
Belief	0.5

Figure 13: Variant 2 Belief Score

Variant 3: Precision Linear Drive

Variant three was designed around the idea of using linear motion instead of rotation while also focusing on precision and control. A linear actuator moves the music sheet instead of the motor to allow smooth and more direct motion. A slot is used for loading the sheet and a solid clip keeps it in place. The load cell helps detect both when the sheet is clamped and when scrolling is complete. To adjust how fast the paper moves, a linear encoder sets the speed, and the tachometer is used to monitor how fast it's actually moving. Directional control is handled by a motion sensor which tracks hand gestures or presence. However, this could be a problem when playing the instrument. Rolling drums help prevent from folding and the frame would help keep the music sheet visible. Sheet removal relies on gravity. Although this design offers high precision and advanced sensing, its belief score did not make it a front runner to move on towards the next phase. The design gave concerns about cost, complexity, and integration of so many high end components.

- Explores non-rotary actuation using linear actuators and load cells.
- Acquires good control of motion and force with high-resolution feedback from the tachometer.
- Options selected towards scenarios requiring smooth positional control over scrolling.

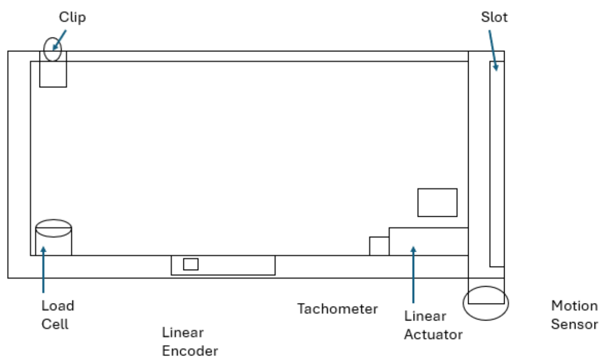


Figure 14: Variant 3 Drawing

Functional Requirements	Variant 3: Ideas
Load Sheet	Slot
Clamp Sheet	Solid Clip
Confirm Clamped	Load Cell
Scroll Sheet	Linear Actuator
Control Direction	Motion Sensor
Set Speed	Linear Encoder
Read Speed	Tachometer
Prevent Folding	Rolling Drums
Provide Visibility	Frame
Scroll To Completion	Linear Actuator
Confirm Completion	Load Cell
Remove Sheet	Gravity

Figure 15: Variant 3 Ideas

Variant 3	Score
Knowledge	0.5
Confidence	0.4
Belief	0.5

Figure 16: Variant 3 Belief Scores

Variant 4: Basic Control

This variant was designed to be straightforward by blending automation with simple manual actions. The sheet is loaded and removed by hand to reduce mechanical issues. A magnet is used to hold the sheet in place. The limit switch would help detect when the clamp is engaged. The actual scrolling would be powered by a DC motor and the potentiometer allows the user to set the speed. The switch would help control direction. To monitor how fast the roller is moving, a hall effect sensor would track the motor's position. The rolling drums were chosen to help the sheets from folding during movement. The holder would keep the sheets in place. Load cell would detect the completion of the scrolling cycle. This design keeps things simple by assigning one reliable component to each function. If it was the chosen variant, it would be relatively easy to prototype, and troubleshoot the music scroller. However, since the belief score was low, a new variant had to be established.

- ❖ Combines automations with manual inputs.
- ❖ Simple implementations by using common components.
- ❖ Aimed to meet all core functions with minimal components per function.

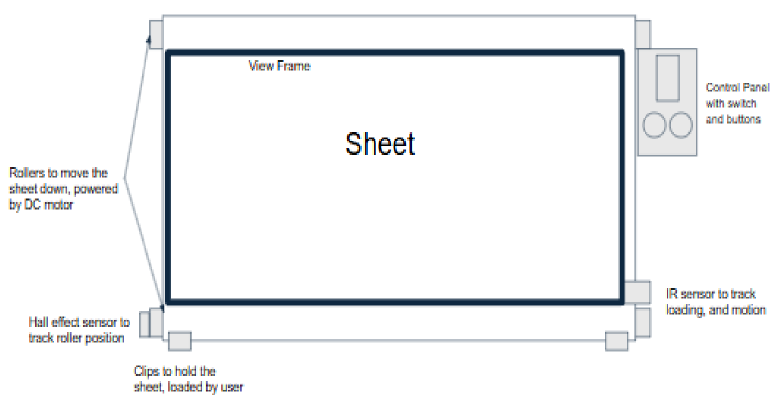


Figure 17: Variant 4 Drawing

Functional Requirements	Variant 4: Ideas
Load Sheet	Direct Human Power
Clamp Sheet	Magnet
Confirm Clamped	Limit Switch
Scroll Sheet	DC Motor
Control Direction	Switch
Set Speed	Potentiometer
Read Speed	Hall Effect Sensor
Prevent Folding	Rolling Drums
Provide Visibility	Holder
Scroll To Completion	DC Motor
Confirm Completion	Load Cell
Remove Sheet	Direct Human Power

Figure 18: Variant 4 Ideas

Variant 4	Score
Knowledge	0.6
Confidence	0.7
Belief	0.54

Figure 19: Variant 4 Belief Score

Variant 5: Sensor Light

This conceptual idea was designed to be sensor light but to still deliver core functionality without relying heavily on complex feedback systems. The tray would be used for loading music sheets, and a solid clip holds it in place. The integrated IR sensor detects the clamping and scrolling of the sheets. The DC motor would handle the scrolling action with a switch being able to control the direction, and the buttons adjusting the speed. Speed would be monitored by a hall effect sensor by providing feedback to ensure the motor is running correctly. Rolling drums help guide the paper, and prevent damage to the sheets. The frame would maintain clear visibility of the music sheet. Sheet removal will be done manually in this design to keep the design mechanically simple. This variant strikes a balance between automation and ease of assembly by using less components.

- ❖ Minimizes sensors while still offering automation.
- ❖ Real time feedback is simplified to a basic circuit.
- ❖ Suitable when feedback isn't essential but functions execution still matters.

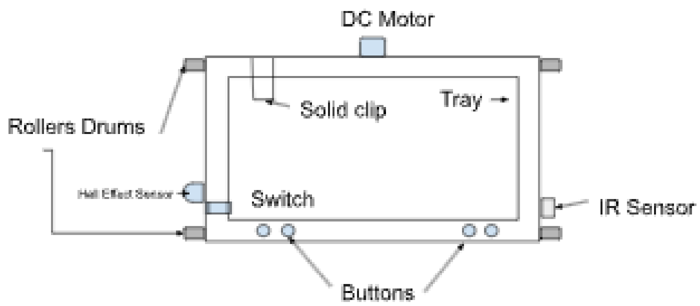


Figure 20: Variant 5 Drawing

Functional Requirements	Variant 5: Ideas
Load Sheet	Tray
Clamp Sheet	Solid Clip
Confirm Clamped	IR Sensor
Scroll Sheet	DC Motor
Control Direction	Switch
Set Speed	Buttons
Read Speed	Hall Effect Sensor
Prevent Folding	Rolling Drums
Provide Visibility	Frame
Scroll To Completion	DC Motor
Confirm Completion	IR Sensor
Remove Sheet	Direct Human Power

Figure 21: Variant 5 Ideas

Variant 5	Score
Knowledge	0.7
Confidence	0.5
Belief	0.5

Figure 22: Variant 5 Belief Score

D. Belief Score Guide Decision

Once the variants were developed from the morphology chart, it was time to measure each variant on how well we thought the design would give a proper solution, and how well did we believe the design would work by using the belief map. Then, we used the belief score equation to quantitatively measure uncertainty.

$$Belief = p(k) * p(c) + (1 - p(k)) * (1 - p(c))$$

where, $(k) = Knowledge$ & $(c) = Confidence$

$$we\ measured\ knowledge\ and\ confidence\ by\ using\ the\ belief\ map,$$

$$Measuring\ knowledge\ (of\ solution):$$

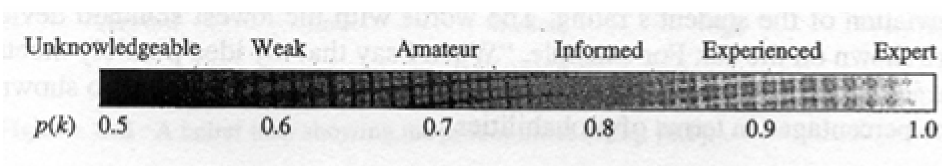


Figure 23: Measuring Knowledge

(From Lecture 3: Morphology Brainstorming)

$$Measuring\ confidence\ (that\ it\ will\ work):$$

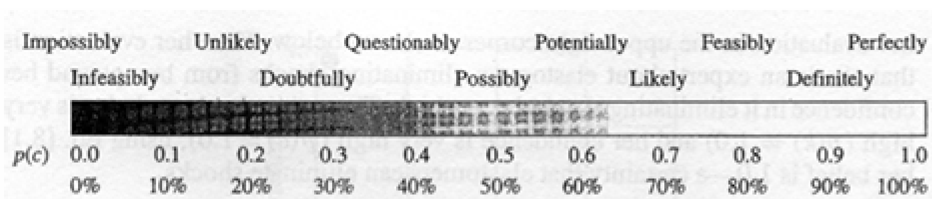


Figure 24: Measuring Confidence

(From Lecture 3: Morphology Brainstorming)

- ❖ **Variant 1:** It has a knowledge (0.8 Informed), Confidence (0.7 Likely), and a belief score (0.62).
- ❖ **Variant 2:** This design had a knowledge (0.6 Weak), Confidence (0.5 Possibly), and a belief score (0.5).
- ❖ **Variant 3**: This variant had a knowledge (0.5 Unknowledgeable), Confidence (0.4 Questionably), and a belief score (0.5).
- ❖ **Variant 4:** Design four was measured at knowledge (0.6 Weak), Confidence (0.7 Likely), and a belief score (0.54).
- ❖ **Variant 5:** Variant five was rated at knowledge (0.7 Amateur), Confidence (0.5 Possibly), and a belief score (0.5).
- ❖ **Variant 6:** the selected variant acquired a knowledge (0.9 Experience), Confidence (0.8 Feasibly), and a belief score (0.74).

E. Selected Variant

Variant 6: Accessible Precision

Variant 6 was chosen for its strong balance between user accessibility and precise system feedback. The music sheet is manually loaded and removed to keep things simple from the mechanical perspective. A magnet is used to secure the sheet while a load cell confirms it is properly clamped in position. A stepper motor was selected for scrolling due to its high accuracy, control capability, and tactile foot pedal to let users set the scroll speed in real time. Direction is controlled through the IR controller which allows the user to not use their hands. A tachometer tracks the scroll speed, and a limit switch detects when the sheet has reached its end. Bearings prevent folding during motion, and a stand ensures clear visibility of the music notes. This design combines feedback components with accessible user inputs like the pedal and IR sensor to provide precise timing and responsive control to make it ideal for users. The belief score for this design was the highest at 0.74 reflecting strong knowledge and confidence in the design.

- ❖ Combines appropriate controls with high precision components.
- ❖ Ensures core functions are addressed with both feedback and user ease.
- ❖ This design is tailored for accessibility and precise timing for musicians needing hands free and responsive control.

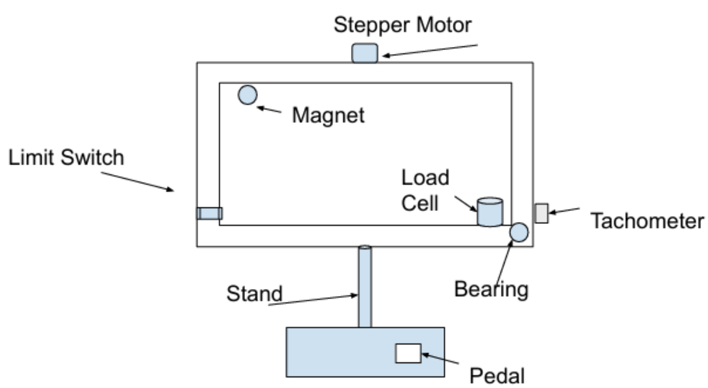


Figure 25: Variant 6 Drawing

Functional Requirements	Variant 6: Ideas
Load Sheet	Direct Human Power
Clamp Sheet	Magnet
Confirm Clamped	Load Cell
Scroll Sheet	Stepper Motor
Control Direction	IR Controller
Set Speed	Pedal
Read Speed	Tachometer
Prevent Folding	Bearing
Provide Visibility	Stand
Scroll To Completion	Stepper Motor
Confirm Completion	Limit Switch
Remove Sheet	Direct Human Power

Figure 26: Variant 6 Ideas

Variant 6	Score
Knowledge	0.9
Confidence	0.8
Belief	0.74

Figure 27: Variant 6 Belief Score

F. Selected Variant Vs Non-Selected Variants

Table 2: Variant 6 vs Others

Selected Variant 6	Non Selected Variants
This variant has the highest belief score: 0.74.	Variant 1 has poor user interaction with hardly any appropriate control.
This variant combines precision feedback with intuitive user-friendly control inputs.	Variant 2 lacked sensors and reliability which made it too manual.

Selected Variant 6	Non Selected Variants
This variant has the highest belief score: 0.74.	Variant 1 has poor user interaction with hardly any appropriate control.
It offers a balanced solution with hands free operation to improve usability for musicians mid-performance.	Variant 3 was technically over designed which would be too expensive for users.
Mechanically reliable while still approachable in terms of production.	Variant 4 had no real advantages over variant 6 since it had fewer features.
It supports hands free, and real time usability making it ideal for musicians.	Variant 5 produced a weak feedback loop, and it had a basic interface.

VI. CAD - DETAILED DESIGN

A. Bill of Materials

ITEM NO.	Description	Vendor	PART NUMBER	QTY.	Cost
1	Linear Motion System Stepper Motor Sensors Assembly	Custom	Linear Motion System Stepper Motor Sensors Assembly V1	1	
1.1	Frame Electronics Assembly	Custom	Frame Electronics Assembly V1	1	$ 14.00
1.1.1			Stepper Motor Assembly V1	1	$ 4.75
1.1.1.1	Stepper Motor	McMaster-Carr Supply Company	6627T92	1	$ 3.00
1.1.1.2	Set Screw Precision Flexible Shaft Couplings	McMaster-Carr Supply Company	4147N168	1	$ 1.00
1.1.1.3	Fast-Travel Ultra-Precision Lead Screw	McMaster-Carr Supply Company	2391N25	1	$ 0.75
1.1.1.4	Low-Profile Mounted Shielded Steel Ball Bearing	McMaster-Carr Supply Company	8600N13	1	$ 0.75
1.1.2	Stepper Motor Bracket	Custom	Stepper Motor Bracket	1	$ 1.25

1.1.3			Frame Assembly V1	1	$ 4.50
1.1.3.1	T-Slotted Framing	McMaster-Carr Supply Company	5537T895_T-Slotted Framing	2	$ 1.50
1.1.3.2	T-Slotted Framing	McMaster-Carr Supply Company	5537T895_T-Slotted Framing	2	$ 1.50
1.1.3.3	T-Slotted Framing	McMaster-Carr Supply Company	5537T935	4	$ 1.50
1.1.4	Bearing Riser	Custom	Bearing Riser V1	1	$ 3.50
1.2	Stepper Motor	McMaster-Carr Supply Company	6627T911_Stepper Motor	1	$5.00
1.3	Ball Screw	McMaster-Carr Supply Company	6624K67_Ball Screw	1	$ 1.50
1.4			Screw Nut Pillow Block V1	1	$ 0.50
1.5	Aluminum Easy-Access Base-Mounted Shaft Support	McMaster-Carr Supply Company	1865K116	2	$ 0.75
1.6	1045 Carbon Steel Rotary Shaft	McMaster-Carr Supply Company	4138N82	1	$ 1.50
1.7	Linear Bearing Housing	McMaster-Carr Supply Company	9804K1	1	$ 0.75
1.8	Linear Bearing Mounting Plate	Custom	Linear Bearing Mounting Plate V1	1	$ 0.50
1.9			Limit Switch Mounting Bracket Stepper Assembly V1	1	$ 1.75
1.9.1	Base Limit Mount Vertical Stepper	Custom	Base_Limit_Mount_Vertical_Stepper_V1	1	$ 0.50
1.9.2	Leg2 Limit Mount Stepper	Custom	Leg2_Limit_Mount_Stepper_V1	1	$ 0.50
1.9.3	Subminiature Snap-Acting Switch	McMaster-Carr Supply Company	7658K223	1	$ 0.75
1.10			Limit Switch Mounting Bracket Side Stepper Assembly V1	1	$ 1.00
1.10.1	Limit Sensor Bracket Side Stepper	Custom	Limit Sensor Bracket Side Stepper V2	1	$ 0.50
1.10.2	Leg Limit Mount Horizontal Stepper	Custom	Leg_Limit_Mount_Horizontal_Stepper_V1	1	$ 0.25
1.10.3	Subminiature Snap-Acting Switch	McMaster-Carr Supply Company	7658K223	1	$ 0.25
1.11			8mm Magnet Encoder Disc Assembly V1	1	$ 0.50

1.11.1	Encased Neodymium Magnet	McMaster-Carr Supply Company	5679K89	1	$ 0.75
1.11.2	Magnet 8MM Encoder Disc	Custom	Magnet 8mm Encoder Disc V3	1	$ 0.35
1.12	T-Slotted Framing	McMaster-Carr Supply Company	5537T282	2	$ 1.50
1.13	T-Slotted Framing	McMaster-Carr Supply Company	5537T895_T-Slotted Framing	2	$ 0.75
1.14			Hall Effect Sensor Bracket Assembly V1	1	$ 0.75
1.14.1	Hall Effect Sensor Bracket	Custom	Hall Effect Sensor Bracket V3	1	$ 0.50
1.14.2	Slot DC Metallic-Object Proximity Switch	McMaster-Carr Supply Company	7092N12	1	$ 0.25
1.15	T-Slotted Framing	McMaster-Carr Supply Company	5537T935	1	$ 0.75
1.16	Button Mounting Bracket	Custom	Button Mounting Bracket_V1	1	$ 0.25
1.17	T-Slotted Framing	McMaster-Carr Supply Company	5537T895_T-Slotted Framing	1	$ 1.00
1.18			SSH1106 OLED Mounting Bracket Assembly V1	1	$ 2.00
1.18.1	SSH1106 OLED Mounting Bracket	Custom	SSH1106 OLED Mounting Bracket_V1	1	$ 0.75
1.18.2	OLED SH1106	Amazon	Oled SH1106	1	$ 1.25
1.19			9CM Proto Board Mounting Plate Assembly V1	1	$ 1.25
1.19.1	9CM Proto Mounting Plate	Custom	9CM Proto Board Mounting Plate V2	1	$ 0.50
1.19.2	Arduino Uno	Amazon	arduino uno	1	$ 0.75
2			Shaft Holder Vertical Assembly V1	1	$ 3.50
2.1	Shaft Holder Vertical Top	Custom	Shaft_Holder_Vertical_Top_V2	1	$ 0.25
2.2	Shaft Holder Vertical	Custom	Shaft_Holder_Vertical_V2	1	$ 0.25
2.3	Shaft Holder Vertical Top Support	Custom	Shaft_Holder_Vertical_Top_V2	1	$ 0.25
2.4	Linear Motion Shaft	McMaster-Carr Supply Company	6112K45_Linear Motion Shaft	4	$ 0.50

2.5			dc motor.step	1	$ 0.75
2.6			Rigid 6 to 8mm Coupler v2.step	1	$ 0.50
2.6.1			Set Screws.step	1	$ 0.25
2.6.1.1			91390A112.step	4	$ 0.25
2.6.2			Coupler.step	1	$ 0.50
3	Shaft Holder Side Assembly	Custom	Shaft Holder Side Assembly V1	1	2
3.1	Shaft Holder Side Bottom	Custom	Shaft_Holder_Side_V1	1	$ 0.50
3.2	Shaft Holder Side Top	Custom	Shaft_Holder_Side_V1	1	$ 0.50
3.3	Linear Motion Shaft	McMaster-Carr Supply Company	6112K45_Linear Motion Shaft	2	$ 1.00
			Total Cost	1	$ 34.75

Figure 28: BOM

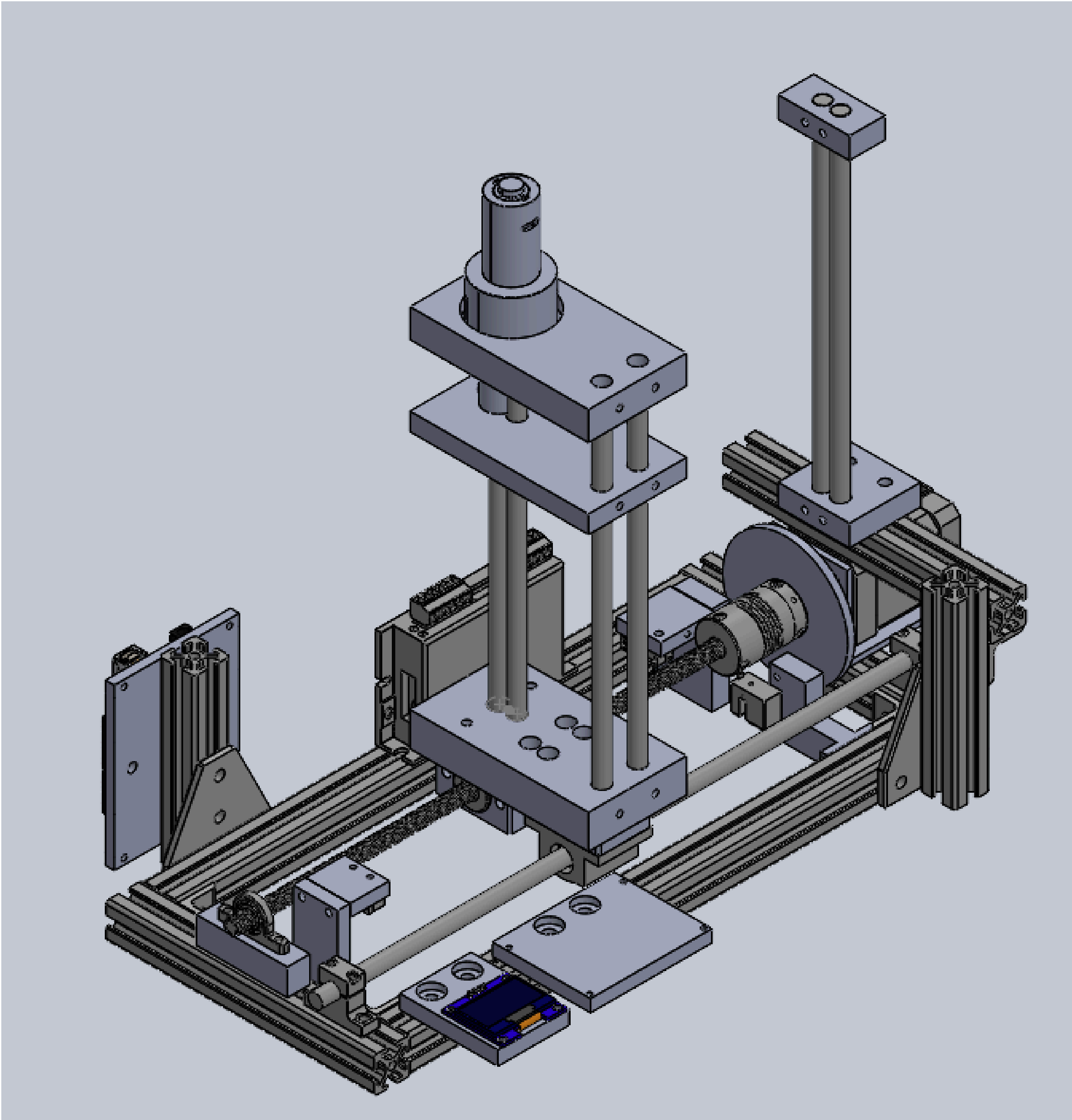


Figure 29: CAD Assembly

B. Top-Level Assembly

This is the assembly of the entire system. As you can see there are various electrical components that comprise our product. The main mechanical components that are in motion are the lead screw and steel rods. The frame consists of aluminum extrusions which provide a rigid framework for our system. Fasteners are used to combine all the parts. Various sensors such as limit switches and hall effect sensors were used to add some feedback to the system. A display and push buttons were used as a user interface and give the user some feedback. As you can see there linear motion is the x direction and rotational motion along the y axis (which is what causes the scrolling). The x direction motion is controlled by a stepper motor which allows for more precise motion while the scrolling motion is provided by a DC motor which rotates more easily and efficiently.

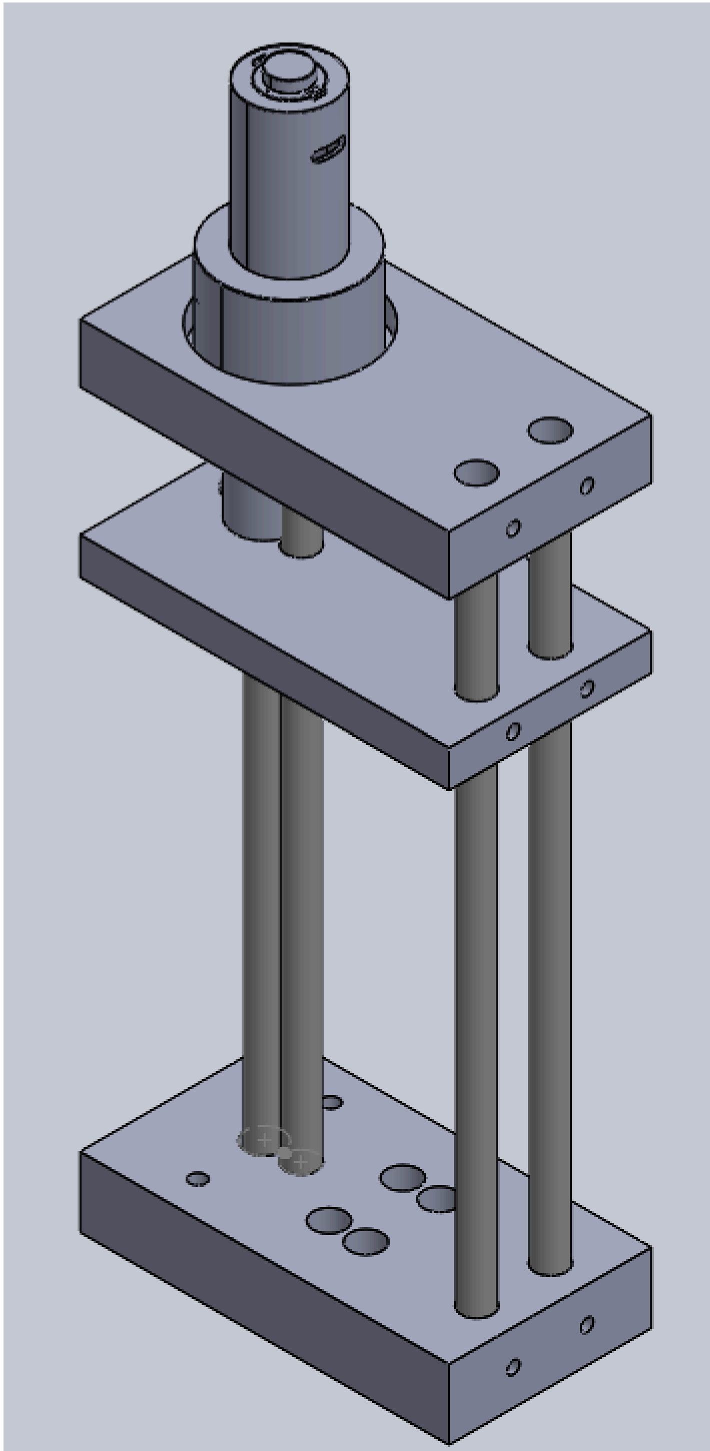


Figure 30: CAD Part

C. Sub-Assembly

In figure ##, the vertical shaft can be seen. This is the section that will house the DC motor. The music sheet will be fed through this part of the assembly and provide power to the scroller, which in turn will turn the page.

D. Feasibility Calculations

Scroll Speed

The feasibility calculations of the sheet music scroller project shows that the system is technically feasible. Using the McMaster-Carr 6627T92 stepper motor, or the NEMA 17, the estimated power consumption is around 10.1 watts, encompassing the motor, the Arduino controller, and even LEDs or switches. At the required scroll speed—about 2.7 revolutions in 1.5 seconds—the motor is comfortably within its rated RPM and torque ratings. This means that it would be able to deliver flawless operation without concerns of overheating or overloading.

Powered from a 12V DC adapter, battery pack, or even an AC wall supply, the system is efficient and able to be operated with adequate runtime. With battery powered units, the operation can sustain for 2-4 hours, depending on the capacity. These calculations substantiate the fact that the device is able to provide smooth scrolling within the power budget and hence is feasible for both portable and even fixed applications.

$$Roller\ diameter\ =\ 1\ in.$$

$$C\ =\ \pi(D)\ =\ \pi(1)\ =\ 3.14\ in.$$

Assuming standard paper size 8.5"x11"

$$Revolutions\ needed\ =\ \frac{8.5}{3.14} \sim 2.7\ revolutions$$

1.5 seconds for scroll speed,

$$RPM\ =\ (\frac{2.7}{1.5})(60)\ =\ 108\ RPM\ <\ 1000\ RPM\ (motor\ capability)$$

Power Requirements

The power requirement feasibility calculation is important as it indicates that the sheet music scroll will function nicely on a 12V power budget. The stepper motor consumes around 0.8 amps using two active stages and will use a load of approximately 9.6 watts. Including the controller

Arduino and small accessories like LED lights or the foot pedal switch, total consumption of power throughout the system would likely still remain below 10 watts. For a wall power DC adapter, this will easily support a ~10W load and offer a continuous runtime. It is a simple and cheap way to provide power to the system.

This low power demand also makes it compatible with a variety of power sources, including compact wall adapters or small battery packs, as mentioned above. In addition, the system stays within standard current ratings for low cost, COTS parts, making it easy to integrate and keep costs low. Overall, the low power demand assists in the ease of use of the design for everyday use without the need for special or high capacity power structure.

$$Motor \ = \ 12V(0.4A) \ = \ 4.8\,W$$

$$2\,active\,phases \ = \ 4.8\,W(2) \ = \ 9.6\,W$$

$$System\,budget\,total \ = \ 9.6W \ + \ 0.5\,W \ = \ {\sim}10.1W$$

Assuming 85% efficiency

With a battery pack that is 12V @2000 mAh, it comes out to be 24 Wh.

$$Runtime \ = \ \frac{24\,Wh}{10.1\,W} \sim 2.38\,hours$$

Step Resolution (Scroll Precision)

To ensure smooth and controlled scrolling, the following calculation is performed to confirm.

$$Roller\,diameter \ = 1\,in.$$

$$Roller\,circumference \ = \ \pi(1) \ = \ 3.14\,in.$$

$$Microstepping \ = \ 1.8°/step\,with\,1/16\,microstepping \ = \ 3{,}200\,microsteps/rev$$

$$Linear\,distance/microstep \ = \ \frac{3.14}{3{,}200} \sim 0.00098"$$

Acoustic Noise and Vibration

To confirm that the noise/vibration levels from the stepper motor will not interfere with the performance, the specs were looked into to verify. The stepper motor is known to produce very minimal noise at low speeds, which is anything that is under 200 RPM, especially with microstepping enabled. Since the RPM that was calculated was around 108 RPM, with a scroll time of 1.5 seconds per activation, the motor is idle, therefore is silent.

Cost Per Unit

To adequately determine the total cost per unit for the low volume CNC machining, the following calculations were added: stepper motor, driver, arduino, power supply, foot pedal switch, plastic housing, and wiring/connectors. The total cost on the lower end is found closer to $62, while on the higher end being $77-$90. This is very feasible for smaller batch runs and can still drop in cost per unit for higher volumes, or by switching to CNC machining.

Thermal Load/Heat Dissipation

To verify that the system will not overheat under continuous or repeated use, the power budget was recapped and used to determine the passive dissipation occurring.

$$Stepper\ motor\ =\ 9.6W\ (85\%\ efficiency\ =\ 1-2W\ lost\ as\ heat)$$

$$Arduino\ \&\ driver\ =\ <1W\ lost\ (negligible)$$

$$Total\ thermal\ dissipation\ =\ \sim 2\ W\ under\ active\ load$$

Small enclosures allow 1-3W of active dissipation without fans, if vented [3]. Through using ABS as the housing, the softening point is around 60-105°C. The thermal load therefore is well within safe passive cooling limits. No fans or heat sinks would be required.

Bending and Buckling

Bending and buckling are two common failure modes when using long, thin beams or rods, as discussed in Lecture 3. It is also highlighted in Skakoon's 6th rule of mechanical design. While both can lead to structural issues, bending is the more likely cause of failure in this design, as the rods are not subjected to significant axial forces. The diagram below illustrates the beam most affected by bending (in red), with the force causing the bending marked in blue.

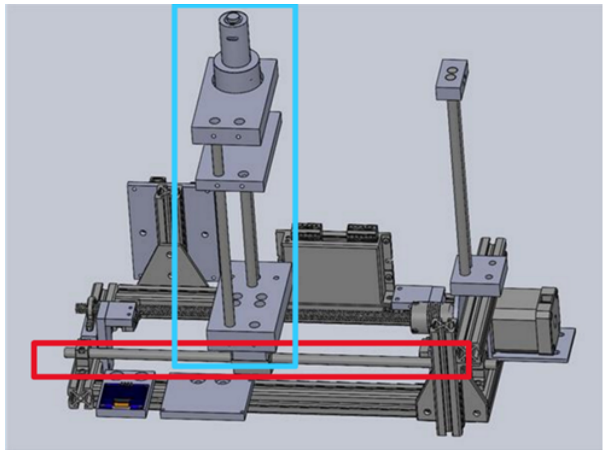


Figure 31: Beam Bending Annotated

Bending stress in the rod is calculated using the equation

$$\sigma = \frac{My}{I} \tag{1}$$

Where M is the moment applied to the rod, y is the distance from the central axis of the rod to the outermost edge, and I is the area moment of inertia of the rod.

To determine the maximum moment, we use the equation

$$M = \frac{FL}{8} \tag{2}$$

Where F is the downward force applied to the rod, and L is the length of the rod. In this case, the Shaft Holder Vertical Assembly has a mass of 255 g, resulting in a force of approximately 2.5 N. Given the design's fixed-rod support configuration, where the Base-Mounted Shaft Supports act as rigid supports, the rod behaves as if it were fixed at both ends, warranting this moment equation.

The area moment of inertia for a solid cylindrical rod is calculated using the equation

$$I = \frac{\pi d}{64} \tag{3}$$

Where d is the diameter of the rod. The rod chosen for the design is an 8mm diameter, 400mm long 1045 carbon steel shaft, which has a yield strength of 620 MPa [1].

Substituting all values into the formulas, the resulting bending stress is calculated to be approximately 2.5 MPa, which is only about 0.4% of the yield strength of the material, resulting in a margin of safety of 247. This indicates that the rod is well within safe limits and is highly resistant to beam failure, ensuring the structural integrity of the design.

E. Tolerance Stackup Analysis

Tolerance analysis was conducted to ensure the shaft holder assembly remained within its tolerance. The Figure and table below display the sub-assembly, height dimensions, and tolerances for each part.

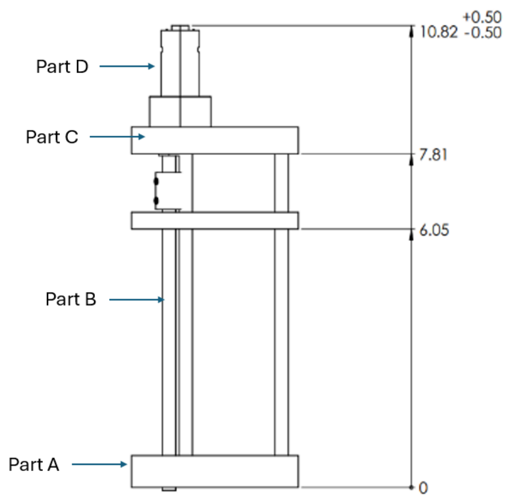


Figure 32: Displays the labeled parts being analyzed for tolerance

Length of	Additive Part A	Additive Part B	Additive Part C	Additive Part D
Nominal	0.630	7.180	0.630	2.380
Tolerance	0.0050	0.0050	0.0050	0.0050
RSS Results	0.0035	0.0035	0.0025	0.0000
Worst Case Tolerance	0.0025	0.0025	0.0025	0.0025

Table 3: Displays the nominal height dimension for each part and the respective tolerances

The chart below displays the Monte Carlo distribution chart. Even under the worst case, the height of the stack will fit in the conservative tolerance of 10.82” +/-0.5”. As shown in the chart, with the tolerances of the parts so low, the assembly passes the Monte Carlo analysis and will function as needed.

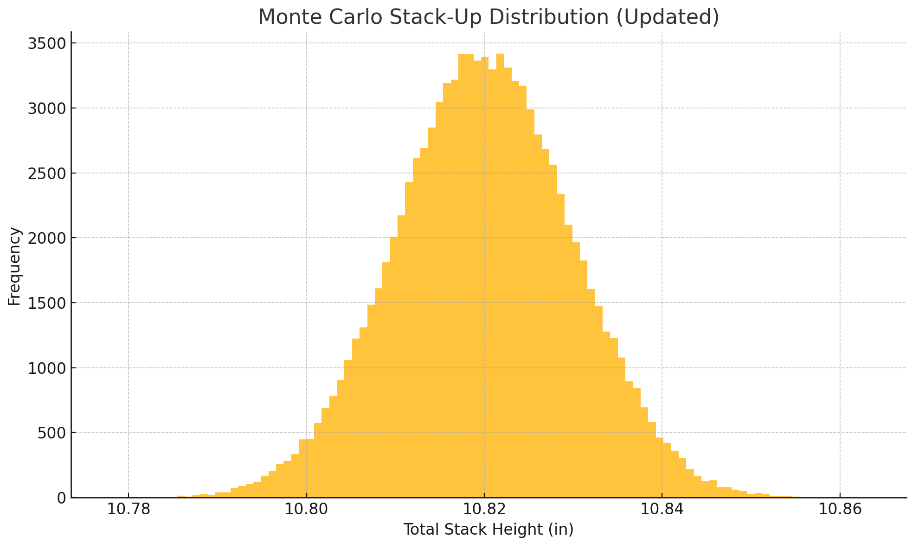


Figure 33. Histogram showing the Monte Carlo simulation results for total stack height. The distribution reflects 100,000 iterations using normally distributed tolerances for each part, demonstrating the likely range and central tendency of the final assembled height.

F. Manufacturing Processes

Injection Molding

Injection molding is a highly effective production process that is capable of producing high volumes of plastic parts with high accuracy and precision. It is known to provide rapid cycle times, uphold tight tolerances, and even have the ability to produce complex geometries. This would typically raise costs using other manufacturing methods, but with injection molding, it does not. After the mold has been made, usually the most time consuming and expensive part of the process, the unit cost drops significantly. This makes injection molding a very cost efficient way to mass produce. The process also minimizes material waste, as stray plastic can often be ground up and reused.

Aside from being efficient and cost effective, injection molding also supports a wide range of thermoplastics, enabling customers to choose a variety of materials with special mechanical, thermal, or chemical properties. In this case, the project is specifically looking into materials such as ABS, PP, or even acrylic. The mold itself would be aluminum, further assisting in keeping costs down. Injection molding also complements automation, which reduces labor cost and enables repeatability for future projects/versions. For clean surface finishes, complex details, or multi piece assemblies, injection molding offers unparalleled flexibility and scalability.

CNC Machining

CNC machining is an excellent choice for production if accuracy, versatility, and flexibility are the primary needs. Unlike injection molding, CNC does not require expensive tooling or molds upfront, which is ideal for low to mid volume production, rapid prototyping, or even specialty components. It offers high accuracy and the ability to machine complex shapes out of solid slabs or blocks of material. CNC machining can also handle tight tolerance callouts as well. CNC machining is able to accept a wide range of materials including metals, plastics, and composites. It compliments well to applications where strength and resistance to heat are necessary.

Another advantage of CNC machining is its quick setup and adaptability. Changes to design can be readily implemented by redrawing the digital model, without the need for any new tooling or non-recurring engineering (NRE). This makes it very effective for iterative adjustments, general upkeep, or even low volume production where flexibility is important. Additionally, surface finishes acquired through CNC processing are better, requiring less post processing. This allows for more time saved.

VII. CLASS PRINCIPLES

A. Application of Engineering Principle #1 - Explicitly Simple

Skakoon's first rule of mechanical design emphasizes the value of simplicity in reducing the risk of failure. When additional systems are introduced, they naturally add complexity, which in turn increases the chance for errors. For example, some of the alternative design parameters that were not chosen introduced additional complex systems. Implementing eye-tracking software to monitor the system's movement would require complex code, which could lead to troubleshooting challenges if something goes wrong. Additionally, using static electricity to clamp the sheet could introduce variability due to environmental conditions, such as humidity, that affect its effectiveness.

In contrast, the design approach chosen for this system is intentionally straightforward: the musician simply steps on a pedal, triggering the system to complete a single action. This simplicity makes the system more intuitive for the user and eliminates the need for complex code, which is easier to manage and debug. By reducing the complexity, this approach not only ensures better reliability but also increases the system's ease of use and maintenance.

B. Application of Engineering Principle #2 - Reduce Friction

Lead screws rely on sliding friction, where the nut moves along the threads of the screw, creating resistance. As Skakoon's 8th design principle suggests, minimizing friction is key to keeping things running smoothly. When friction is present, it can cause stick-slip motion. This is when the nut sticks, then suddenly slides, making its movement jerky and unpredictable. For this device, precision matters, so this type of movement can leads to several issues.

During a performance, this can result in unwanted noise which can be distracting for both the performer and the audience. If sheet music starts shaking due to the friction, it makes it much harder to follow the notes. Additionally, the extra stress this puts on the system can wear it down faster, leading to premature failure.

To combat this, applying a high-quality lubricant to the lead screw helps cut down on friction, allowing the nut to move smoothly and consistently. Along with lubrication, tighter tolerances help prevent the nut from rocking or wobbling during movement. This eliminates some of the jerky motions that occur when there's too much play in the system.

To make sure everything stays in working order over time, it's would be advantageous to encase the lead screw system. This prevents dirt and debris from getting in and degrading the lubricant, keeping everything clean and running smoothly. This protective casing helps maintain the system's performance while extending its lifespan, giving users a much more reliable and quieter experience.

C. Application of Engineering Principle #3 - Load Path Considerations

Some general rules of thumb for load paths fall under Skakoon's 4th principle of Mechanical Design. The Sheet Music Semi-Automated Scroller design effectively applies the principle of efficient load paths through several key features.

First is the foot-pedal load path. The foot pedal provides a direct, simple, and short triangular load path, ensuring the force from the user's foot is quickly and intuitively transferred to the system. This minimizes the need for additional components and maintains a compact load path in one plane, reducing potential failure points and making the system more reliable.

Another example is the motor-to-sheet load path. The stepper motor transfers motion directly to the sheet through a rigid frame and aligned components, eliminating unnecessary intermediate parts and encouraging precise motion. Additionally, bearings placed close to the motor reduce friction and prevent bending, allowing smooth, controlled sheet scrolling.

The overall design ensures that the load paths are short, direct, in a plane, and easily analyzed, creating a stable and efficient system that minimizes wear and simplifies maintenance.

D. Application of Engineering Principle #4 - Use of Bearing

The application of bearings is used to help reduce the rotational friction and provide support to radial and axial loads. This principle comes from Shigley's chapter 11 Rolling-Contact Bearings and Week 12 Lecture - Bearings. The purpose of bearings is to reduce frictional loads. In our design the application of bearings is used primarily to reduce the radial friction between our stepper motor shaft and maintain alignment with the shaft axis. In general, bearings should be placed as close as possible to the applied load to minimize unsupported shaft length and reduce bending. When choosing the type of bearing, the load type, speed of rotation, available space, and environmental exposure are all factors that need to be taken into account. As shown in our design, we used a low-profile mounted shielded steel ball bearing because it is compact, capable of supporting the necessary load from our motor shaft, and includes shielding to protect against contaminants in the open-frame environment. We also have to take into account the way the bearing is mounted and the configuration whether it is easily integrated with our custom bearing, allowing for the shaft to be kept aligned with minimal assembly complexity, following our application of engineering principle 1. Bearings in general are commonly used across mechanical systems, where rotational accuracy and load management is crucial. In our case, we chose a ball bearing over others due to its low friction coefficient, reduced energy consumption, minimal maintenance, and increased efficiency [2]. Ultimately, our choice in our bearing is dependent on the needed precision, durability, and modularity of our system, supporting the key designs objective and reinforcing our application of our bearing mechanical design principle.

E. Application of Engineering Principle #5 - Component Alignment Matters

In design, ensuring that parts are aligned ensures that the design and finished product will help in maintaining the performance, minimizing wear, and preventing failure of the final product. This principle is discussed in Shigley's chapter 7, specifically the sections on shaft design for stress and limits and fit. These sections highlight how misalignment of the shafts can introduce bending stress, unwanted vibrations and excessive friction, all of which shortens the lifespan of the design. In our project, this principle was applied when designing our shaft and motor placements. We needed to align our stepper motor, shaft coupler, and screws. precise alignment is necessary to ensure smooth torque transfer from the motor to the screw. Even the smallest deviation from misalignment can cause our design from an optimal lifecycle to a shaft that deflects over time due to excessive loads on the bearings. We also had to ensure that the linear motion shafts and bearing houses were mounted properly and parallel to the frame. Misaligned guide shafts may lead to jamming or uneven sliding resistance, especially since our system has multiple linear bearings. During assembly, we had to make sure that care was given to each and every part, using jigs and making sure everything is aligned properly. This minimized the need for over constraining the design and the need for forced fits. A key note to understand here is that even if the design on paper is thoroughly and properly toleranced, the components will fail if the parts are not properly aligned. This leaves us with the key principle that proper alignment will make the design either succeed or fail. If properly aligned, the design will allow for a long life cycle, long-term reliability, and reduce wear and energy loss due to unintended friction. In conclusion, applying this principle of component alignment matters ensures that the overall mechanical design of our system runs smoothly, reduces stress and friction, and provides a better overall system efficiency.

F. Application of Engineering Principle #6 - Tolerancing for Assembly and Fit

Precise tolerancing is essential to any mechanical system design. It ensures that the parts of the design will be able to be assembled correctly, move smoothly, and maintain alignment during operation. This principle is discussed in week 14 lecture Design for Assem DWG, as well as in Shigley's chapter 1-14 Dimensions and Tolerances and in chapter 7-8 Limits and Fits. In this chapter it states that the designer is allowed to adopt any geometry of fit for holes and shafts that will ensure intended functionality. Using tolerancing, after making our design, we can ensure not only that our design fits, but it can also provide proper clearance and interference fits for rotating and sliding components. Tolerancing not only ensures dimensional accuracy, but also it ensures that the final assembly functions as intended without any problems, such as loose ends or wobbling. In our project, we applied this principle to ensure that our linear motion shafts and their corresponding bearing housing allows for smooth linear motion while avoiding excessive wobbling. We made sure to match our dimensions based on standard fit tables and ensure that our shaft could slide without sticking and without rattling. Tolerancing was also crucial in the area of making sure our guide rails were aligned properly. Even the most minimal misalignment could lead to binding during motion. This is especially important since our guide rails were part of the main motion of our stepper music flipper. If the linear bearings were not mounted within an acceptable flatness and tolerance, motion could have been stalled completely. Tolerancing was used in many parts of our design, primarily to allow for reduced stress and increased usability. A general rule of thumb is use clearance fits for rotation and interference fits if it is fixed. By applying tolerancing, we were able to prevent mechanical binding, reduced friction and overall increase ease of assembly. In conclusion, this principle would ensure that our mechanical system performance would be without any constraints, theoretically reduces wear and ensures consistency across repeated builds.

VIII. PROTOTYPE

Below you see the team's prototype that was based on our CAD. It meets many of our functional requirements and design parameters. Construction was straightforward but it did require more wiring than what is noted in the CAD. Functionality is satisfactory and we get the scrolling action that we need.

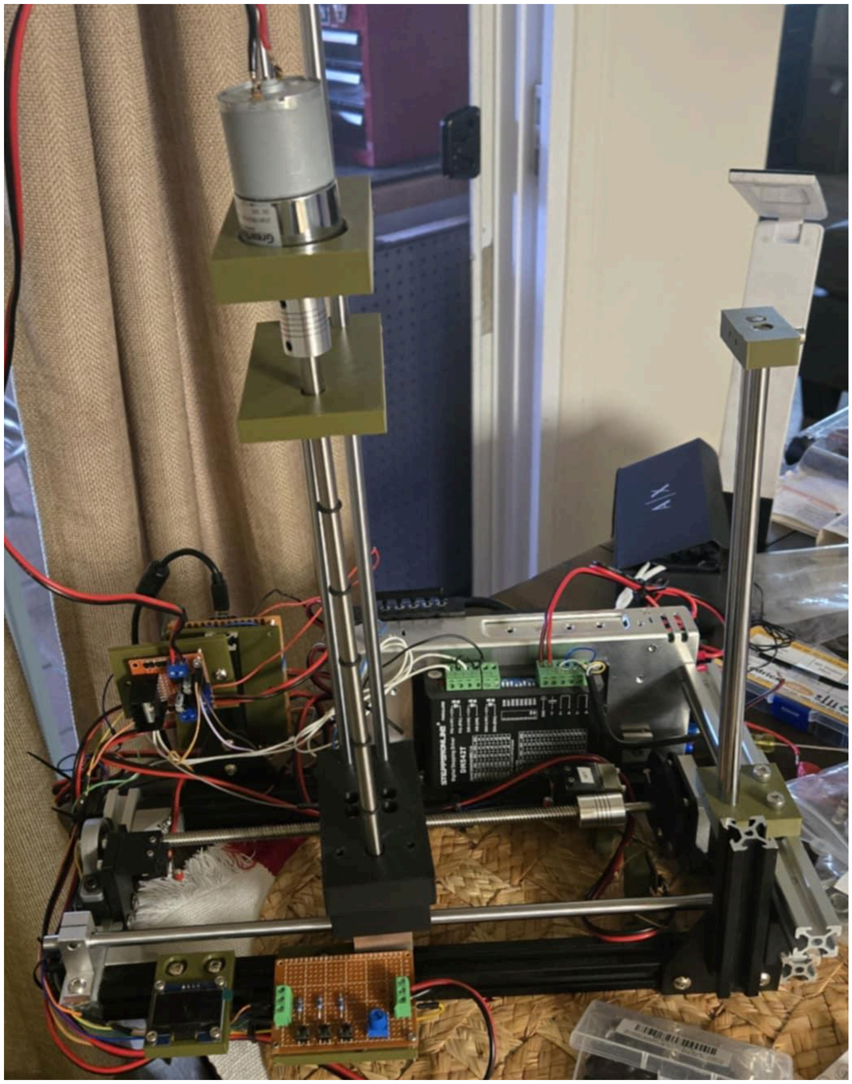


Figure 34. Prototype

IX. CONCLUSIONS

A. Summary Comments

In this report, we developed a music sheet page turner product design out of unaddressed customer needs observed via an ethnography study. These observed needs were then refined, and formed into functional needs via functional maps which were used to generate a morphology chart of various design parameter solutions for each functional need. These needs were developed into 6 different variant designs, which were then compared to choose the option we as a team had the most belief in. This design was then turned from a concept into a detailed prototype design. To do this we implemented several design principles from class and conducted feasibility calculations to check the design. The design was detailed via CAD and drawings in which critical tolerance stack ups were checked. The design was finally produced as a prototype, making use of cots hardware where possible and 3d printed parts for rapid production.

B. Discussion

Working through the project as a large group was a challenge. Coordination and active communication was key to moving the project forward. Additionally, many of the project tasks built on the others and so required collaboration to progress things. With everyone's varying schedules and location this was a challenge that thankfully we were able to navigate. For design development in industry this is generally less of a problem based on basic work hours and possible co-location but could come up for teams across varied sites and timezones.

It was also tricky to translate some things from the chosen to a prototype version, as not everything that conceptually was part of the variant could easily be achieved within the time frame for prototype development or within our capabilities for manufacturing. Much of our parts ended up being 3d printed, allowing for rapid production, and for our frame we made use of 80-20 which gave a lot of adjustability and helped account for possible assembly issues.

Finally, while this class is mostly mechanically focused, our product utilized a good deal of electronics for motors, motor control, and sensors, requiring interdisciplinary knowledge. There was also a large amount of wiring required to connect all of these components, which was a challenge to manage.

C. Recommendations

The biggest recommendation we have would be to have active project management in order to coordinate the project and the group. This could include timelining, work breakdowns, and milestone targets. This would help keep things organized, on track and progressing, and is a big part of product development beyond just the technical aspects. While not the most organized of groups, things generally progressed well for the project due to the efforts of our team members but that may not always happen and setting up initial planning and structure can remove some of that risk.

Another recommendation would be to develop an intermediate prototype as suggested in class.This could be made from legos or just be a mock-up of a key system or any other variety of options as described in class. This can help inform design decisions for the higher fidelity models as well as provide early feedback into areas to pay attention to in the future. While the timeline for the project is somewhat truncated, making efficient use of everyone’s time, effort, and focus is incredibly important so any smaller things that can efficiently contribute to the success of your product are critical to take advantage of.

D. Conclusions

Overall, our prototype implemented our design variant effectively and gave us the desired scrolling action desired by customers. Based on our calculations and testing, this prototype could be progressed and refined into a feasible product. For a relatively simple topline concept, it was interesting to see the product fleshed out and how many class principles and concepts we ended up using including motors, bearings, design for assembly, gears (via the lead screw), and more.

Interestingly it does not seem that there are many similar mechanical products out there and available, with other options mostly being digital applications to try to do similar things. For most of our design process the focus was on functionality, i.e. getting the core functions to work, and we think further refinement should come to usability to make it easier to use and more attractive to customers. With that further variant development could come from adding specific usability needs to our functional maps and the variant could then be refined using a similar design process as what we implemented to get to this prototype.

The design also implements a lot of electronics, and so this project became very interdisciplinary from wiring them all up and in coding the controller to get the product to function. That is also true of a lot of mechanical engineering in the real world, as there are only a few types of products that are entirely mechanical or even amongst that list don't interact with other disciplines throughout product development. This makes interdisciplinary knowledge critical and makes understanding how mechanical systems interact with each other and other systems critical to being a successful part of an engineering team. But, in order to be successful working with other types of engineers, understanding the baseline mechanical functionality and design is a prerequisite to then being able to translate that to larger products.

E. Future Work

For the future of this product, several improvements should be made in order to develop it into a viable, sellable design. Firstly, the prototype packaging should be heavily focused on. Currently we have a lot of free wiring to be secured and hidden. Additionally, many of our parts are 3d printed or COTS 80-20, so should be redesigned for higher rate options such as injection molding on the plastic parts and machined or stamped parts for the frame. As part of this redesign, a lot of the parts could be miniaturized and the overall system weight reduced which would make the product more consumer friendly. More testing needs to be done on the system to improve and smooth its functionality as well as being analyzed for any user safety systems or controls that should be put in place. Another option to consider would be studying electrical architecture as currently it is AC powered from a wall plug in power supply, but the product may be better suited for dc powered from batteries. And finally, the design variant should be examined for cost reductions, either from reducing part count or for interrogating the design parameters chosen for either cheaper alternatives or cheaper ways to implement the chosen options in order to reduce the overall product cost to make it an attractive consumer option.

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