Simplifying Part Access

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Contents:

1. Introduction

1.1 Problem

Printed circuit board designs, even at the prototype/hobbyist level, can use a significant number of small components. Typically, these components are packaged in a reel of paper/plastic “tape” with cutouts for each component and a removable film to hold the components inside the tape. The film can be peeled back to remove a few, but it is very easy to accidentally peel it too far and lose a lot of parts. Thus, the preferred way of working with tape-and-reel packaging is to cut the tape to the required length for the project, leaving the film intact on the rest of the reel.

This in itself poses a problem, though. If a project needs more than a few of the same part, manually counting to find the cut point becomes very tedious, with a higher likelihood of making a mistake, and ending up with the wrong number of components.

1.2 Solution

A way to approach this problem would be designing a modular system where the end user can request a specific number of parts from a reel, and it feeds the required length of reeled components out. This can be accomplished using a tileable design where each tile is a box that holds a reel of the desired components. The tape on the reel is pulled by a stepper motor, and the sections are cut by a motorized blade. To confirm that the correct number of components are dispensed, an IR sensor is used to measure the movement of the tape.

1.3 Visual Aid

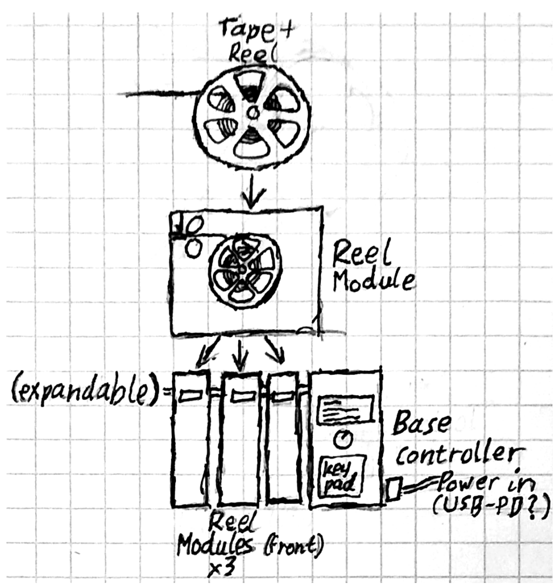

Figure 1: Illustration of proposed overall solution

1.4 High-Level Requirements

- Movement/Sensing - The system should be able to accurately measure out the correct number of components when given the correct component spacing and clocked properly. Movements should be accurate to +/- 1 mm of the requested position.
- The system should have a successful yield rate of 90% at the minimum to ensure that in large quantity orders, parts are not wasted. At least 90% of the time the cutting process dispenses the right quantity of the components with clean cuts and doesn’t damage any of the components.
- The system should accept the most common reel diameters (7 inch/178 mm and 13 inch/330 mm), and it should support tape widths up to at least 25 mm, and tape depths up to at most 4 mm.
- The base controller should be able to support at least 3 reel modules. It should supply enough power to drive 3 reel modules simultaneously, and it should disable additional modules so that power limits are not exceeded. (We are currently planning on building 3 reel modules, so the power-limiting behavior can be tested by reducing the limit to 1 or 2).

2. Design

2.1 Block Diagram

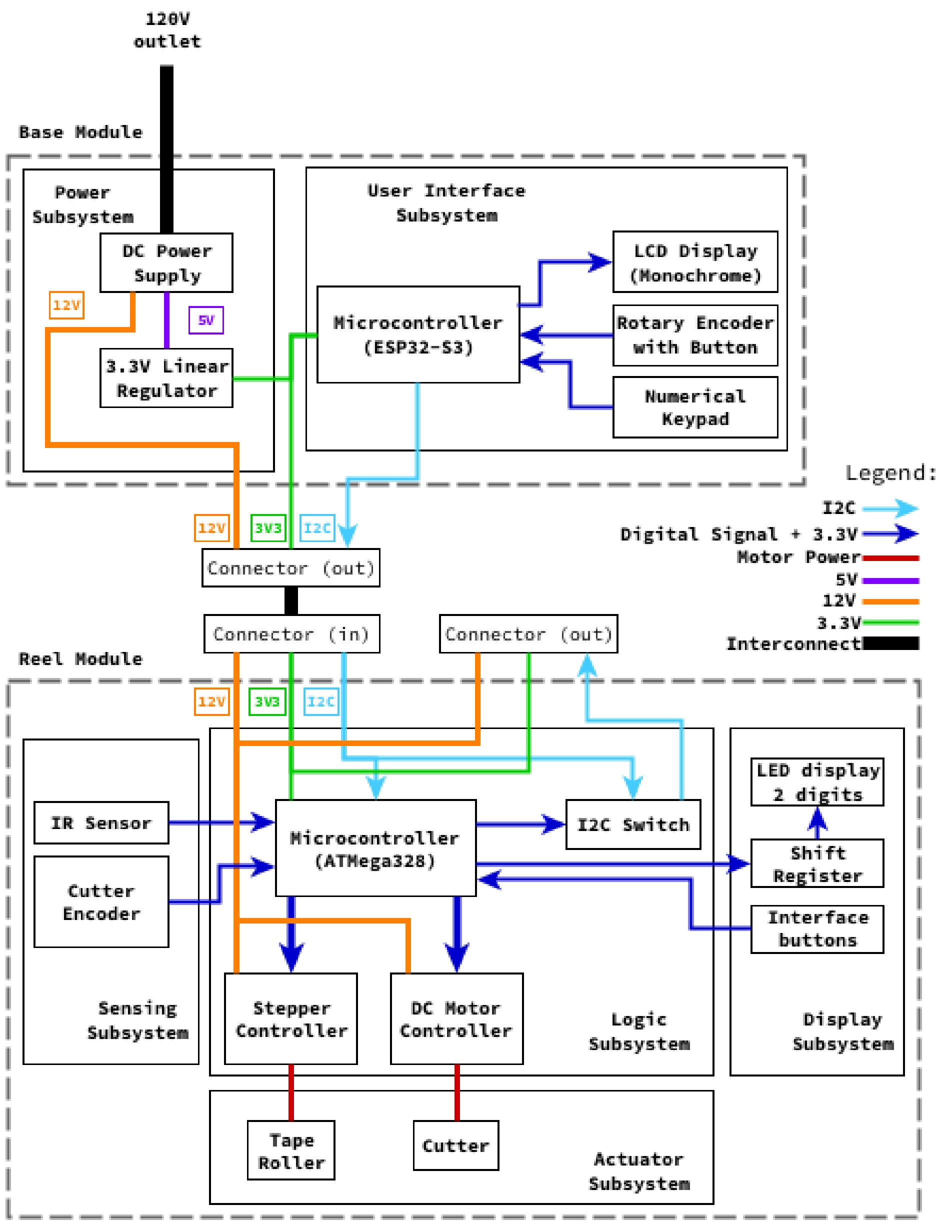

Figure 2: Diagram showcasing individual circuit components of proposed design

The device has two distinct subsystems that can be distinguished as the Base Controller and the Reel Module. The Base controller has all the components that a user will interact with. It has input for power and regulates it to ensure all the components get the right voltage. The LCD screen and keypad allow the user to send commands, select components and quantity to be dispensed. All of this will be parsed by an ESP32 onboard the subsystem and the specific commands sent to the ATMega328's for each Reel Module. Inside each reel module, a stepper motor will pull the reel a predetermined distance to push out the right quantity of components which will be verified by an IR sensor using the sprockets in the reel as reference. Once it's verified, the cutter powered by a motor will slice the reel and dispense the components.

2.2 Subsystems

2.2.1 Power Subsystem

2.2.1.1 Power Supply

Requirements: Estimated ~60 W power requirement for 3 modules:
3.3 V (+/- 0.2 V tolerance) required for logic power (can regulate from 5 V or more if needed). Power requirements:

- ATMega328 = 6 mA x3 = 18 mA
- A4982 stepper driver = 8 mA x3 = 24 mA
- DRV8231 motor driver = 4 mA x3 = 12 mA
- 2x 7-segment LED displays (per reel module) = 5 mA x16 x3 = 240 mA
- ESP32 = 100 mA peak
- USB-PD controller = 3 mA
- Display = 37 mA
- Various other current sinks = 10 mA
- Total = 444 mA (1.47 W at 3.3 V)

12 V (+/- 10%) needed for the steppers and controllers. Power requirements:

- 12W per stepper
- 7W per cutting motor

We are using a Mean Well RD-85A supply to provide DC power to the device from a power outlet. This provides 85 watts of power as 12 V and 5 V outputs, and we can use a standard LM1117 linear regulator to produce our 3.3V logic supply. Since these components have very well-defined voltage/current specifications, no additional requirements/verifications are needed for this subsystem.

2.2.2 User Interface Subsystem

Requirements:

- LCD display capable of alphanumeric text. This will show the state of any active operation and allow the user to input settings and start new operations.
- Rotary encoder + button interface to navigate menus and scroll the display
- Numerical keypad to manually enter spacing dimensions and other calibration data

Nice-to-have:

- SD card and/or USB port with mass storage capability to upload BOM files for component counts

Requirements	Verification
● The ESP32 can enumerate the attached reel modules on the I2C bus ● The ESP32 can communicate with the attached reel modules on the I2C bus ● The ESP32 can detect communication errors and fail safely	● Connect a reel module or microcontroller with reel module simulation software to the I2C bus ● Connect the system to 3.3V power. ● Verify that the ESP32 enumerates the connected module ● Verify that the ESP32 correctly reads the module's configured component type. ● Disconnect the module and verify that an error is reported
● The LCD shows a summary of the status of each reel module, specifically: ● the component type ● the number of components to cut ● the number of times to repeat ● status (active/idle/error) ● position in the daisy chain. ● If an error status is present, the component information should be replaced with an error message. ● If no modules are attached, the display should show a "No modules attached" message. ● Each summary should be one line of text, and up to 4 can be displayed on screen without scrolling.	● Connect the system to 3.3V power with no reel modules. ● Verify that the LCD displays "No modules attached". ● Disconnect power, add a microcontroller with a reel module simulation program to the I2C bus, and reconnect power. ● Verify that the LCD shows the appropriate information when: ○ A job is set up with 10 components repeated 5 times ○ The job is started ○ The job finishes ○ An error occurs
● The ESP32 can read the rotary encoder and keypad	● Connect the system to 3.3V ● Upload an input test program ● Verify that the controller can differentiate between left and right turns of the encoder

	• Verify that the controller can detect when the encoder's button is pressed • Verify that the controller correctly reads the button when a single button on the keypad is pressed.

2.2.2.1 LCD

Newhaven display with specs of 128x32 graphical pixels, monochrome, and backlit. [1] This will display summary information for all of the modules, as well as menus to configure and control the machine. The details of the menu operation will be detailed in the algorithms section.

2.2.2.2 Rotary encoder

Generic clicky knob encoder with integrated switch and D-shaft; we can 3D print a knob for it. [2] This will allow the user to scroll on the summary page and select a reel module to configure.

2.2.2.3 Numerical keypad

Standard 12-button keypad with 0-9, *, and #. [3] This will allow the user to enter numbers for component spacing and other parameters.

2.2.2.4 Main Processor

Requirements:

- Control the user interface
- Enumerate the reel modules on startup
- Send commands to the reel modules via I2C
- Read the status of the modules
- USB port available for programming and (possibly) mass storage

Nice to have:

- Provide a local web interface to send settings and files to the base controller

We are going to use the ESP32-S3 module because of its low cost, I/O pin count, and Wi-Fi option (although this is not a requirement for the project). Microcontrollers with similar performance and pin count typically cost significantly more. [4]

2.2.3 Reel Module - Logic Subsystem

This subsystem controls reel feeding, cutting, and component counting.

2.2.3.1 Microcontroller

We are using an ATMega328PB microcontroller to drive the reel modules. These combine reasonable pin count and processing power at a very low price point. They can be run at 3.3V if the clock frequency is reduced from 20 MHz to 12 MHz.
The most important criterion for using this chip is whether it has a sufficient number of pins. We can determine the number of pins required to control the system:

Pin Number	Function	Assignment
PB0	ICP1/CLKO	Cutter encoder A
PB1	OC1A	Cutter encoder B
PB2	SS0/OC1B	ISP header, SS pin
PB3	MOSI0/TXD1/ OC2A	ISP header, MOSI pin
PB4	MISO0/RXD1	ISP header, MISO pin
PB5	XCK1/SCK0	ISP header, SCK pin
PB6	XTAL1/TOSC1	Crystal oscillator
PB7	XTAL2/TOSC2	Crystal oscillator
PC0	ADC0/MISO1	12V sense
PC1	ADC1/SCK1	IR sensor
PC2	ADC2	Interface button 1
PC3	ADC3	Interface button 2
PC4	ADC4/SDA0	I2C bus SDA
PC5	ADC5/SCL0	I2C bus SCL
PC6	RESET	Reset button
PD0	OC3A/RXD0	Stepper driver STEP
PD1	OC4A/TXD0	Stepper driver DIR
PD2	INT0/OC3B/ OC4B	Stepper driver ENABLE
PD3	OC2B/INT1	I2C switch enable

PD4	XCK0/T0	Display digit select
PD5	OC0B/T1	Motor drive H-bridge IN2 (PWM)
PD6	OC0A/AIN0	Motor drive H-bridge IN1 (PWM)
PD7	AIN1	Display shift register SHIFT
PE0	SDA1/ICP4/ ACO	Display shift register STORE
PE1	SCL1/T4	Display shift register DATA

Pin names/descriptions sourced from [11].

Requirements and Verifications:

Requirement	Verification
● Can communicate with the base module over I2C at 400 kHz	● Attach a reel module to a working base module ● Apply 3.3V power to the system ● The device should be enumerated over the I2C bus and should be shown on the base module display.
● Can send pulses to the stepper driver at a consistent rate (frequency should not deviate more than +/- 5% when running at a constant speed).	● With the stepper motor attached, probe the stepper coil voltages with an oscilloscope. ● Attach a reel module to 3.3V and 12V power. ● Use the on-board interface to command the module to dispense 100 components. ● Verify that the frequency read by the oscilloscope does not fall outside the specified tolerance.
● Can save reel configuration and calibration to the chip when powered off	● Attach the reel module to 3.3V power ● Set the component spacing to a non-default value (5mm for example) using the on-board interface ● Cycle power to the reel module ● Use the on-board interface to verify that the spacing is the same

2.2.3.2 I2C switch

To enumerate the modules on the I2C bus, we employ an I2C bus switch so that additional modules do not respond to enumeration requests until it is their turn. More information will be provided in the algorithms section.

2.2.3.3 Stepper and DC Motor Drivers

For the stepper motor driver, we are using the Allegro A4982 chip, as it has sufficient current output for our NEMA-17 stepper and supports up to 16x microstepping (if additional resolution is required). This chip has STEP and DIR inputs to command the stepper, an ENABLE input to start/stop commanding the stepper, and a RESET input, which can be connected to the microcontroller's reset pin. [12]

For the DC motor driver, we are using the DRV8231 H-bridge driver for its low cost and current capabilities. This chip has a basic digital signal interface to control each side of the H-bridge:

IN1	IN2	OUT1	OUT2	DESCRIPTION
0	0	High-Z	High-Z	Coast; H-bridge disabled to High-Z (sleep entered after 1 ms)
0	1	L	H	Reverse (Current OUT2 → OUT1)
1	0	H	L	Forward (Current OUT1 → OUT2)
1	1	L	L	Brake; low-side slow decay

To control the speed, the inputs can be toggled between a directional command and braking; using PWM, the active duty cycle can be adjusted continuously. [14]

2.2.4 Reel Module - Actuator Subsystem

This subsystem consists of the cutter and feeder actuators.

2.2.4.1 Feed Stepper Motor

Requirements:

Requirement	Verification
● Maximum feed rate of at least 5 mm/s	● Apply 3.3V and 12V power to the reel module ● Command the module to cut 100 components ● Measure the distance moved and time to calculate the feed rate
● Tape feed positional accuracy of at most +/- 0.5 mm	● Cut 10 individual components ● Measure the width of each cut component and verify that it is within tolerance
● Sufficient torque to pull tape from the reel, especially at low speeds	● Apply 3.3V and 12V power to the module ● Command the module to cut 1 component ● Verify that 1 component is cut from the tape, the stepper motor does not stick, and the tape does not slip.

Nice to have:

- Tape feed positional accuracy of +/- 0.25mm to support very closely packed components

After some deliberation running calculations on a different motor to determine the precision needed, as discussed in the later tolerance analysis, we decided to settle on a smaller NEMA17 motor that should provide the necessary precision. [9]

2.2.4.2 Cutter

Requirements:

- Maximum 2 second cut time
- Maximum of 1 cut failure in 10 consecutive tests
- Can reliably cut paper and plastic tape without jamming (under the above test parameters)

Nice to have:

- Much lower rate of cut failures (ideal but potentially difficult/expensive to test)

We decided upon a gear motor with a rotary encoder for this [13]. The gear motor will rotate a standard utility blade attached to it, acting as a pivot and hinge, similar to that of a paper guillotine. Due to the risk of a blade and motor together, we plan to have it mostly enclosed so fingers cannot get in and risk getting injured, while also providing a kill switch to immediately cut power to the entire system.

Requirements	Verification
• Motor can cut through the the tape reliably within the span of a couple seconds	• Apply power, use the interface to command 10 cut operations of consistently length, and verify that the cutter does not jam, and cuts cleanly. • To provide efficiency, time cuts to ensure that once the motor is initiated, each takes a maximum of 2 seconds to cut.
• Confirm that the blade safety mechanism is working	• Make the opening only slightly larger than our tape, only 10mm in height, and confirm that someone can not reach their finger inside. • Ensure that the kill switch immediately cuts power to the motor, and that it slows down. Can confirm by taking slow motion video on a phone and frame peeking to compare the time required for a complete rotation before and after cutting power to the motor.

2.2.5 Reel Module - Sensing Subsystem

This subsystem contains the sensors to measure tape motion and cutter position.

2.2.5.1 Tape Sensor

Requirements:
- Detects the sprocket holes in the tape
- Can locate the edges of the sprocket holes to within +/- 1 mm when feeding at a slow (1 mm/s) rate
- Can reliably (max 1 failure out of 100) detect sprocket holes in black plastic and paper tapes

Nice to have:
- Can detect sprocket holes in clear plastic tape

Tentatively choosing an optical sensor from DigiKey [6] but may need to change to one with different dimensions.

Requirements	Verification
• The IR sensor can distinguish between the tape and a sprocket within the tolerance of ±1%.	• Ensure that nothing is in between the IR sensor module and then record the boolean value from the ATMega328’s. • Pass tape through it and record the value when the tape is blocking the IR path. Ensure that it is different from the initial value. • Move the tape so a sprocket is now in between the transmitter and receiver. Confirm that the value is the same as the default value.

2.2.5.2 Cutter Motor Encoder

The cutter motor has a built-in magnetic quadrature rotary encoder to report changes in position to the microcontroller. The encoder produces two square-wave pulses 90 degrees out of phase from each other. Depending on the direction of rotation, the phase of the first signal will be ahead of or behind the second signal, which allows the microcontroller to keep track of the absolute position even if the direction changes.

2.2.6 Reel Module - Display Subsystem

The reel module will have an integrated 2-digit numerical display and a pair of buttons to allow the user to send basic commands to the reel module without needing a full base controller. Additionally, the LED displays will provide the immediate status of the reel module itself if it has lost communication with the base controller.

Due to limited pin count on the ATMega chip, we are using a standard 74HC595 shift register to drive the 7-segment displays. An inverter on the “select” pin allows the microcontroller to switch between the two digits using a single output pin.

2.3 Algorithm Description

This device has several important algorithms that will be described below.

2.3.1 Display Menus

The main screen consists of individual lines providing information about the attached reel modules. This can be navigated by turning the encoder knob. Clicking the button when selected on a reel module will enter the settings for that module. If a cutting job is set up on any of the reel modules, a “Run” option will appear to allow that job to be started. While the job is running, this button changes into a “Cancel” button to stop the operation; individual module settings cannot be changed in this mode.

The settings screen allows the user to change the component spacing and set up a cutting job (component count, repeat count) for the module. This screen will have an exit button to return to the main menu.

These menus will be subject to change in the future if more settings are added or found to be useful.

2.3.2 Enumeration Algorithm

When several reel modules are attached to the base, they would be virtually indistinguishable from each other, as they are all on the same I2C bus and have the same address. We resolve this by adding an I2C switch and an enumeration system so that when the system boots, only one module is visible on the bus. From here, the base module can assign a unique I2C address to this module and move on to the next one. The communication protocol is as follows:

- The reel module boots in “enumeration” mode, waiting for an ID from the base controller. There should be a mechanism (analog switch or I2C buffer) to disable communication passthrough to the next connected module until this device has been enumerated.
- The base controller sends an ID to the first connected module, and then the module re-enables I2C passthrough so that the next module (if any) can be enumerated. Already-enumerated modules ignore the ID assignment command.
- The base controller can then send commands (update settings, dispense components, etc.) to the reel modules.
- The reel modules respond to requests for status.

2.4 Tolerance Analysis

This device needs to align the cut position within +/- 1 mm of the expected position. In order to do this, we need the resolution of the stepper motor to be small enough to achieve this accuracy. Our current choice of stepper motor has a specified 7.5 degree stride[5], and the stepper driver has support for 8 levels of microstepping[7]. We can calculate the angular resolution θ_M with N levels of microstepping and stride θ_S as:

$$\theta_M = \frac{\theta_S}{N} = \frac{7.5°}{8} = 0.9375°$$

From this, we can determine the maximum wheel radius that will allow our angular resolution:

$$s = r(\pi \times \theta_M)/180 = 0.5\,mm$$

$$r(0.016) = 0.5\,mm$$

$$r = 30.55\,mm$$

Having a larger wheel radius gives us additional pulling force from our stepper torque. We can use the upper bound from this result to determine the trade-off between torque and resolution when choosing exact parts and dimensions.

After doing these calculations, we realized our initial stepper motor choice was of convenience without enough research behind it, so we did more work and found one [9] that has a specified 0.9 degree by default, which would allow us to reach our desired level of precision without microstepping as further research has suggested that microstepping can be rather finicky. That said, we can always do a very minor amount of microstepping if we need to refine it further, but while these calculations told us that the precision was originally possible, they also helped us find a better option for even better expected results.

3. Cost and Schedule:

3.1 Cost Analysis

The total cost for parts is listed in the figure below before shipping comes out to $210.94. With 5% shipping and tax as 10% as seen in previously submitted projects, it would be $242.58 for parts. Using the 2.5 rule for lab with an estimated $35/hr for 150 hours we expect the project to take across team members, that leaves us with 2.5 * $35/hr * 150 hrs = $13,125 labor cost. Together the total cost of this project is $13,125 + 242.58 = $13,367.58.

Description	Manufacturer	Quantity	Price	Link
Nema 17 0.9 degree stepper	StepperOnline	3	$10.66	Link
LM1117IMPX-3.3/NOPB	Texas Instruments	1	$1.14	Link
RD-85 12V/5V power supply	MEAN WELL USA Inc.	1	$32.28	Link
128 x 32 Monochrome Display	Newhaven Display Intl	1	$12.82	Link
Rotary Encoder	Bourns Inc.	1	$1.92	Link
12 Button Keypad	SparkFun Electronics	1	$4.95	Link
ESP32 board	Espressif Systems	1	$3.48	Link
IR Sensor	SHARP/Socle Technology	3	$0.68	Link
Stepper Motor Driver	Allegro Microsystems	3	$3.65	Link
PLA filament to print misc. parts	Overture	1	$18.99	Link
ATMEGA328PB-ANR	Microchip Technology	3	$1.85	Link
Razor blade for cutter	Blades	1	$6.85	Link
DC Motor Drive	Texas Instruments	3	$1.52	Link
Gear Motor	uxcell	3	$18.49	Link
7-segment display	Lite-On Inc	6	$1.75	Link
Schmitt Inverter Chip	Texas Instruments	3	$0.29	Link
Mosfet Array	Toshiba Semiconductor	3	$0.24	Link
Shift register	Nexperia USA Inc.	3	$0.46	Link
IC Driver	Texas Instruments	3	$1.27	Link

Still need proper measurements for box logistics.

3.2 Schedule:

Week	Task	Person
October 2nd - October 8th	Order and gather parts for prototyping	Everyone
	Start PCB Design	Aidan
	Research Stepper motor control	Matheu
	Research interfacing with IR Sensor	Tejas
October 9th - October 15th	Finish PCB design and pass audit	Aidan
	Test Motor behavior to feed reel	Matheu
	Initial testing of IR Sensor with reel	Tejas
	PCB order October 10	Everyone
October 16th - October 22nd	Revise PCB design	Everyone
	Prototype cutting mechanism	Tejas
	Prototype Control box	Aidan
	Start assembling main box prototype	Matheu
	PCB order October 17	Everyone
October 23rd - October 29th	Revise PCB design	Everyone
	Finalize cutting mechanism	Tejas
	Finalize Control box	Aidan
	Continue Assembly	Everyone
	PCB order October 24	Everyone
October 30th - November 5th	Initial full Test of reel module. Adjustments as needed	Everyone
	Work on UI for control box	Tejas & Matheu
	Work on implementing tileable nature (IC2)	Aidan
November 6th - November 12th	Finalize details of first module	Everyone
	Assembly additional two modules to be able to showcase tiling.	Everyone
November 13th - November 19th	Final touch ups and demo prep.	Everyone
November 20th - November 26th	Fall break, work on wrapping up and final touches only if needed.	Everyone
November 27th - December 3	Demo	Everyone

4. Ethics and Safety:

Primary possible safety concerns associated with this project would be if the cutter is exposed and poses risk of injury, or if the cutter fails and poses risk of injury while fixing. The easiest fix to the former would be to enclose the cutter so that it is not exposed for an individual to get cut by. Since a slot is needed to feed components out of the machine, this should be made small enough that fingers cannot fit into it. Similarly the latter can be approached by making sure we have a power shutoff switch such that the motor for the cutter cannot engage while attempting to fix any issues with it.

As such the safety manual for such a device is relatively simple, whenever hands are near the cutter, make sure the kill switch is engaged such that the blade cannot spin on power and risk injury. Similarly, if any jams or issues occur, make sure the kill switch is enabled before accessing.

That said, on the matter of Ethics, there are no clear ethical risks or violations we are worried about, as we are not dealing with any sort of private information, or conflicts of interests, while we also agree to seek honest criticism as specified by IEEE 7.8 I.5 [8]. Similarly, we also will make sure we work together as a group both for our group, along with the TA and other students and individuals we work with to treat others fairly as specified by IEEE 7.8 II [8].

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