PORTABLE AUTOMATED MACRO-STITCHING FILM DIGITIZER

ECE 445 Design Document | Spring 2026

Project #23
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1. Introduction

1.1 Problem

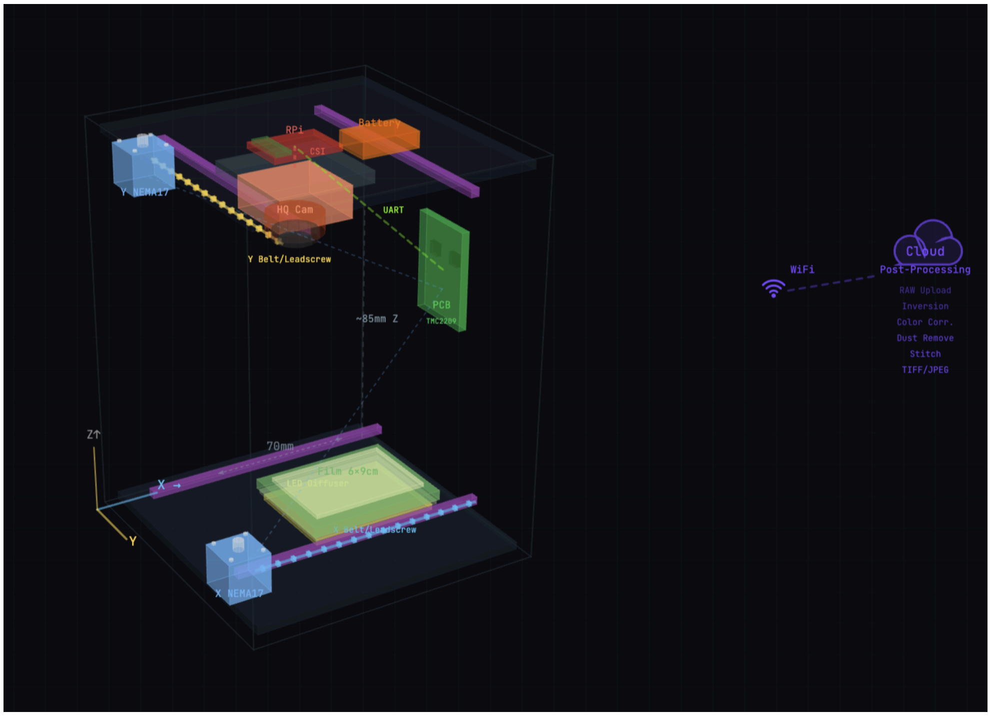
The resurgence of analog photography has created a technological gap: capturing images on film is desirable for its aesthetic, but digitizing them for online distribution is inefficient. Enthusiasts currently face a "trilemma" where professional drum scanners are prohibitively expensive and bulky, flatbed scanners are slow and lack resolution for small formats, and "DSLR scanning" requires complex, non-portable setups involving copy stands and precise alignment. There is currently no portable, standalone device capable of automatically digitizing multiple film formats (35mm and 120 Medium Format) into high-resolution images without a tethered PC.

1.2 Solution

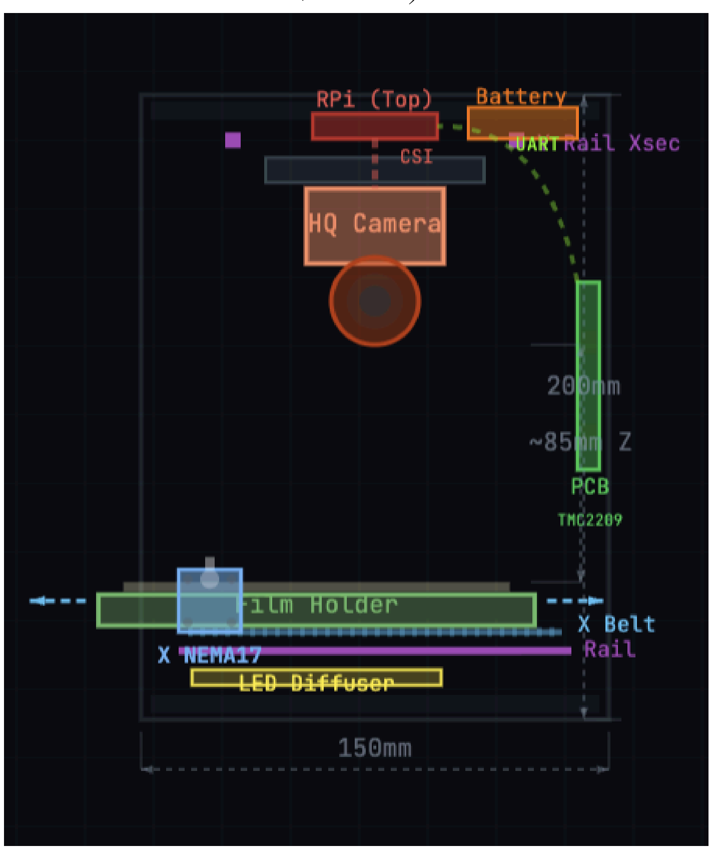
We propose an automated film digitizer contained within a portable enclosure. Unlike traditional scanners that use a linear line-scan sensor, our solution will utilize a “macro-stitching” technique [1]. This involves using a high quality camera with a macro lens setup to capture multiple high-fidelity sub-images of the film and performing computer vision processing to compose a final image.

The film carrier will be mounted on a repurposed precision X-Y linear stage, which has been motorized using modified servos. A microcontroller will coordinate the motion and lighting capabilities needed to capture several images covering the entire area of film. A Raspberry Pi 4 will handle the actual image capture functionality and will use OpenCV algorithms to stitch the sub-images into a single 4K+ resolution photograph [1]. This hybrid approach aims to achieve professional archival quality in a portable form factor.

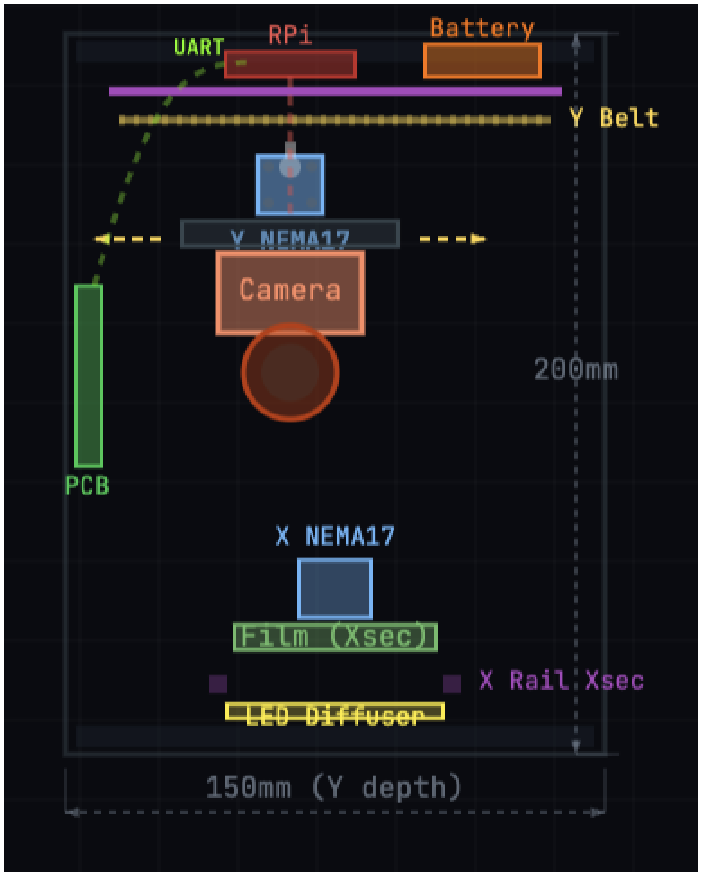
1.3 Visual Aid



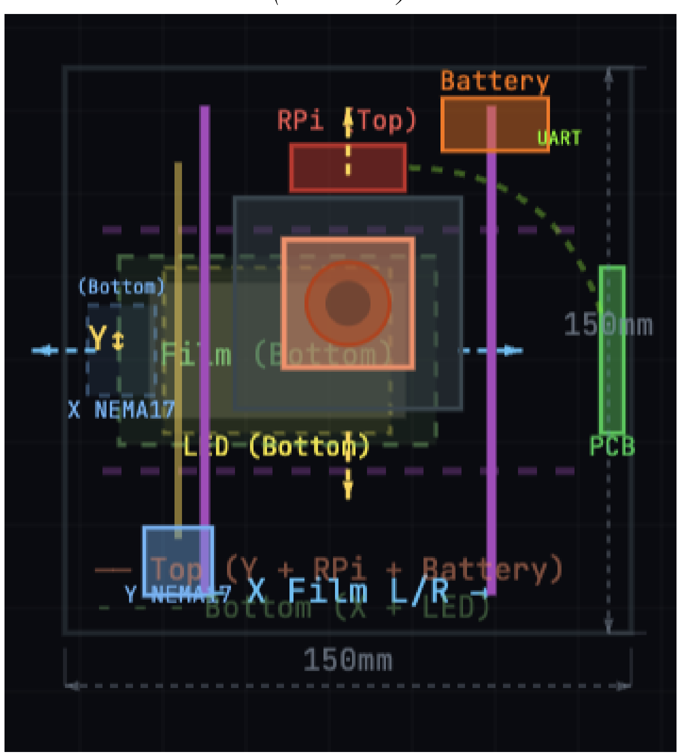
(3-D view)



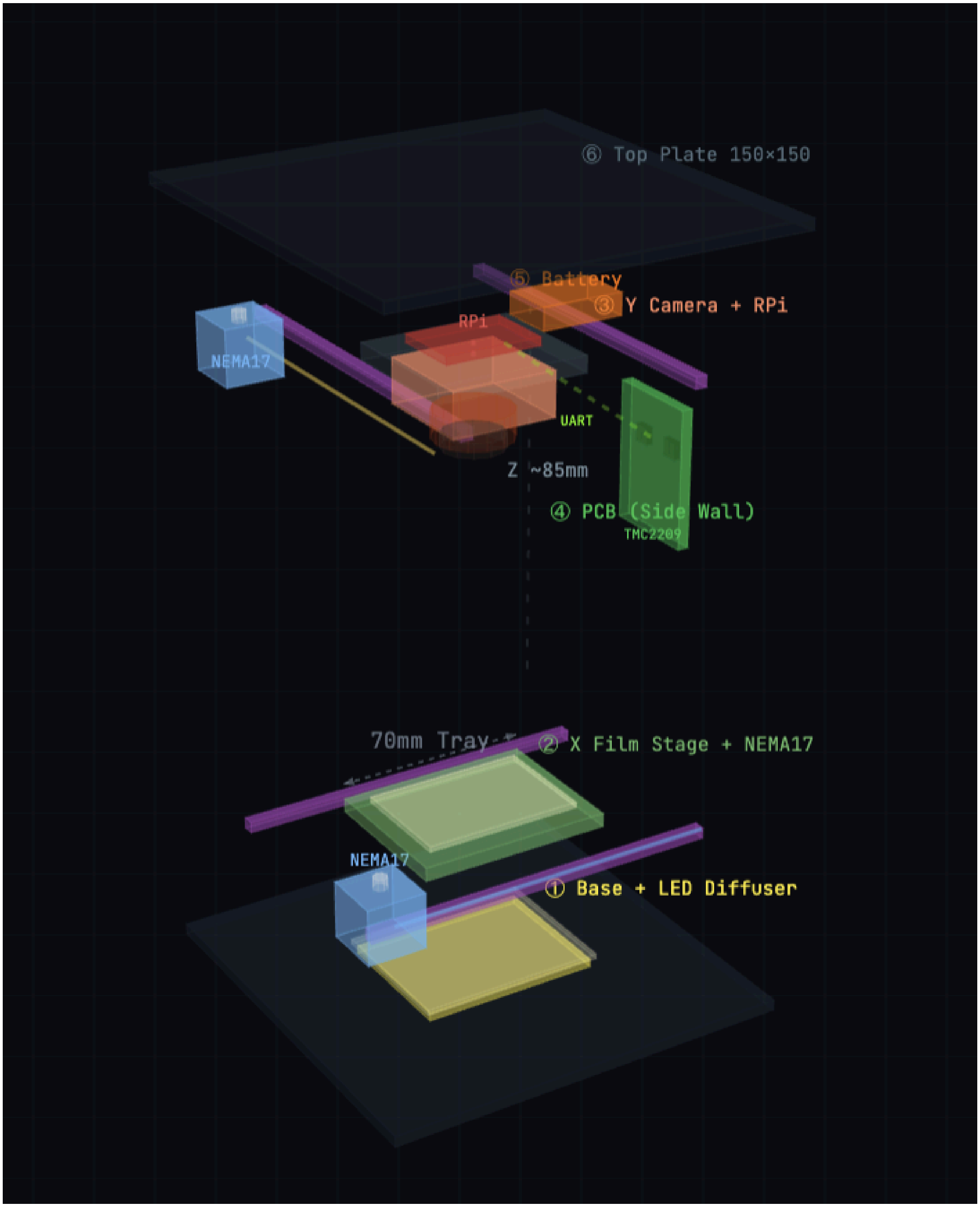
(Front-View)



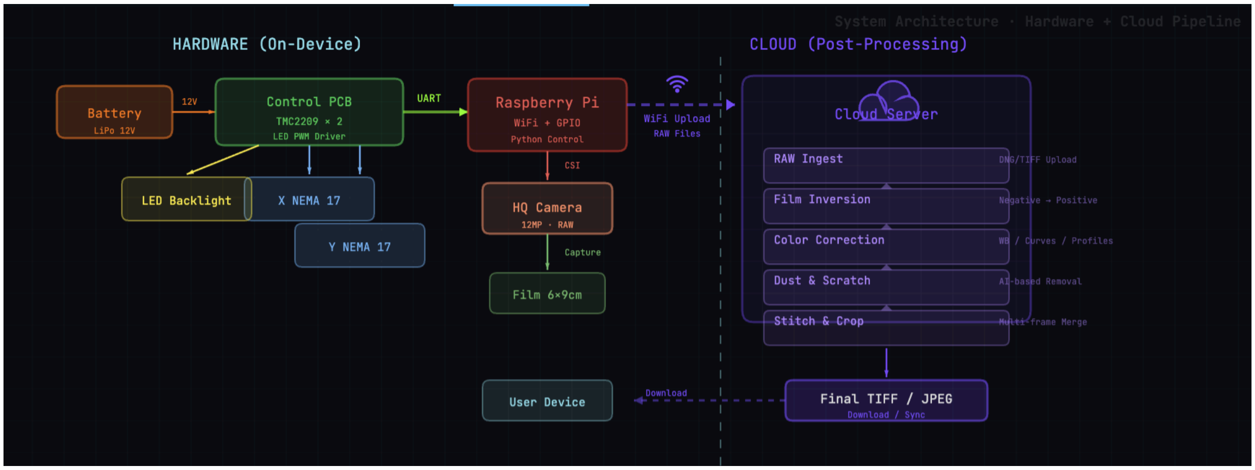
(Side-View)



(Top-View)


⑥ Top Plate 150×150
⑤ Battery
③ Y Camera + RPi
RPi
NEMA17
UART
Z ~85mm
④ PCB (Side Wall)
TMC2209
70mm Tray
② X Film Stage + NEMA17
NEMA17
① Base + LED Diffuser

(Split-View)



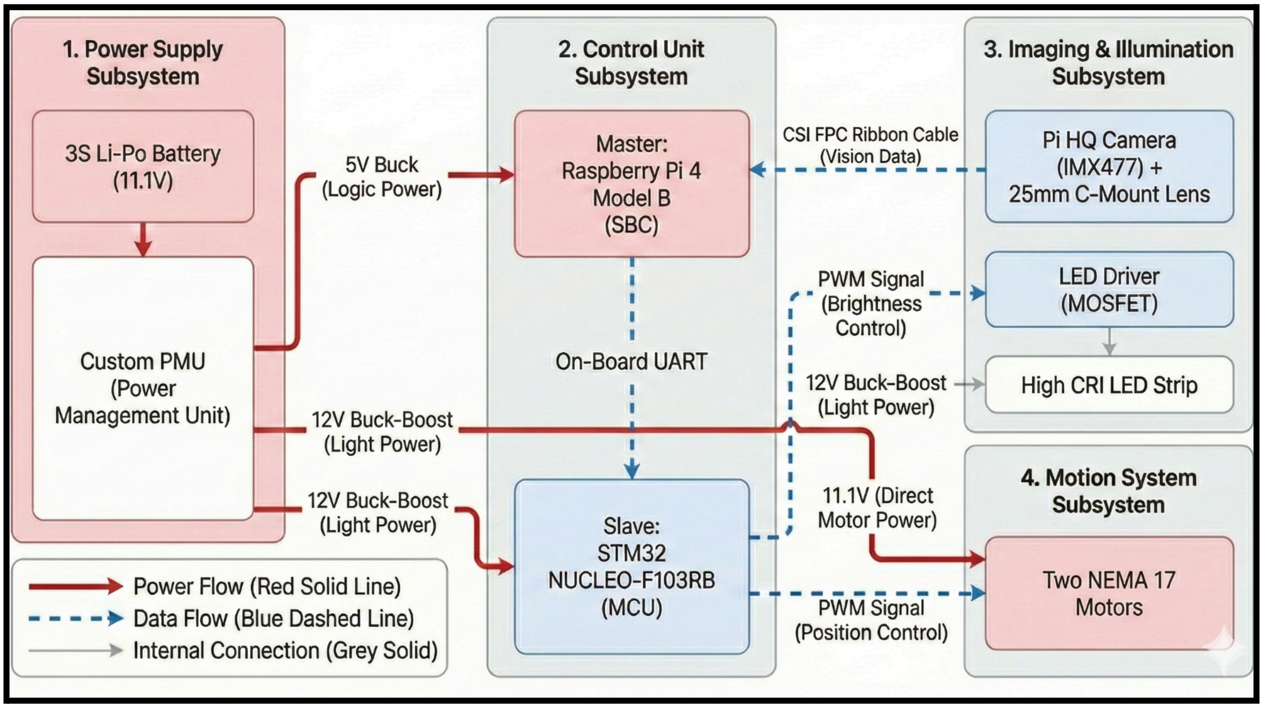
(System Architecture)

1.4 High-Level Requirements

1) Resolution and Stitching: The system must produce a final image with a minimum resolution of 3840x2160 pixels (4K) by autonomously moving the film stage to capture and stitch at least 4 overlapping macro frames with an alignment error of less than 5 pixels.
2) Portability: The complete device, including power, optics, and mechanical parts, must fit within a physical volume of 15cm (L) X 15cm (W) X 20cm (H) and weigh less than 1.5kg to meet our portability requirements.
3) Automation Speed: The system must complete the full cycle of automatic exposure, X-Y scanning, image capture, and software stitching for a single frame in under 30 seconds without human intervention.

2. Design

2.1 Block Diagram



2.2 Physical Design

Mechanical dimensions and placement of sensors and actuators are included in the Visual Aid.

2.3 Subsystems

2.3.1 Power Supply and Management

The power subsystem will manage energy distribution from a 11.1V 3S Li-Po battery. We will utilize a star topology design to isolate noisy motor loads from sensitive logic signals. The design also includes regulated rails for logic and LEDs, along with a battery management system for charging and protection.

Requirements	Verification
Regulate 11.1 battery input to 5V± 0.25V for logic components and 12V± 1V for motor drivers under a load of 100mA to 2000mA	Connect battery to input and measure output rails using a multimeter under no load and full-load
Isolate motor noise from logic signals using star topology. Voltage ripple should not exceed 50mV peak-to-peek while motors are running.	Use an oscilloscope to measure voltage ripple on logic rail when motors are under peak current draw.

2.3.2 Motion System

The motion subsystem is responsible for precisely positioning the film unit and camera in 2-dimensional space in order to take pictures at specified positions within the area of the film. We will use a precision translation stage with two Nema-17 motors connected to the stage's micrometer knobs via custom 3D-printed couplers. The STM microcontroller will drive these motors to perform the row-by-row scanning pattern required for image stitching.

Requirements	Verification
Achieve a minimum translation resolution of 1 mm += 0.5mm per step using Nema-17 motors.	Issue a command to move the motor for a set number of steps (such as 50 or 100). Measure the physical displacement of the linear stage using a caliper and verify that it matches the desired theoretical displacement.
Execute a row-by-row scanning pattern across a film-sized area and verify that the stage returns to the origin position with a maximum variance of 0.25mm.	Confirm that the stage can run through a scan and return to the starting position for a full reset.

2.3.3 Imaging and Illumination

The imaging subsystem consists of a high quality camera and 25mm lens used to achieve a macro field of view at a distance of 8.5cm from the film. A custom LED backlight array will also be used to provide illumination, with brightness being controlled via pulse-width modulation from the microcontroller in order to accommodate different film densities. Specifically, we will use a High-CRI transmissive array and a glare-controlled reflective array.

Requirements	Verification
Maintain a consistent focal distance of 8.5cm ± 1mm between the lens element and the film surface to ensure high output image quality.	Mount the camera and lens, capturing a test image at the specified distance and visually inspect image clarity.
Adjust backlight brightness using PWM and avoid artifacts during image capture.	Capture images at different PWM duty cycles (such as 10%, 50%, 90%) and inspect frames for artifacts or image deformities

2.3.4 Cloud Processing Pipeline

In addition to onboard computer vision processing on the Raspberry Pi, we will also employ cloud resources to efficiently handle compute-intensive post-processing tasks. This will consist of negative inversion, denoising, sharpening, and any additional steps such as LLM-augmented generation. The algorithms will be executed as Python script(s) running in a serverless compute environment on a cloud provider such as Amazon Web Services to keep costs low and have minimal off-device dependencies.

Requirements	Verification
The serverless compute environment must be able to execute a Python image processing pipeline to perform negative inversion and denoising with sub 30-second latency per image, with a 5-second margin of error.	Make requests to cloud endpoints with raw images and inspect logs to verify that end-to-end latency is below the target threshold. Use a timing library to record end-to-end latency.
The server needs to expose an API interface that the Raspberry Pi can use to upload raw camera data and receive the end result.	Perform HTTP Post requests from the Raspberry Pi controller process with sample images. Verify that the service returns a success message upon receipt and a valid URL to the processed output image.

2.3.5 Control Unit

The control unit consists of a STM32-series microcontroller and onboard Raspberry Pi 4B, which will act as the master controller.

The microcontroller will act as the real-time hardware controller to handle output signal generation for the motion control and lighting components. It will receive high-level position commands from the Pi via serial communication.

The Raspberry Pi will handle the user interface, which allows users to start scans and retrieve results following post-processing. It will use the libcamera software library to interact with the camera, and coordinate captures with outgoing motion control instructions in order to take multiple pictures of the source film. Following the physical capture process, it will run OpenCV algorithms to stitch the captured images into a final 4K output image.

Requirements	**Verification**
The Raspberry Pi needs to synchronize camera captures through libcamera with motion commands to the microcontroller. It needs to ensure that the stage is stationary during a capture to prevent motion blur. The capture will need to be taken 500ms ± 50ms after the last motor pulse is issued.	Use a logic analyzer to monitor the control signals from the Pi and the pulses issued from the microcontroller to the motors. Verify that the delay between the last pulse and the capture signal is large enough to avoid motion blur.
The STM32 needs to interpret serial commands from the Raspberry Pi and generate motor and LED output signals with low latency. The STM32 must issue a motor pulse within 10ms ± 2ms of receiving a completed control command.	Manually issue movement commands through a serial console. Use an oscilloscope to measure the end-to-end transmission time and evaluate against the threshold.
The image stitching algorithm on the Raspberry Pi needs to successfully combine multiple overlapping frames into a single 4K (3840x2160) image with no visible discontinuities or alignment errors (> 5 pixels ± 1 pixel).	Run the capture sequence on a test image (perhaps a printed grid). Inspect the stitched output to visually verify that there are no alignment issues. Use a calibrated ISO 12233 resolution chart and measure pixel offset at stitch boundaries using an image editing tool.

2.4 Tolerance Analysis

To ensure the Portable Multi-Format Film Digitization System delivers reliable, high-resolution results within its compact footprint (15cm×15cm×20cm), the system must account for mechanical, optical, and electrical variances.

Mechanical & Motion Tolerance

The system relies on an automated X-Y feeding mechanism to align the film (moving up to 1.2 cm x 1.5 cm) beneath the camera sensor.

Stepper Motor Accuracy: The NEMA 17 stepper motors have a step angle of 1.8◦ (200 steps/revolution) with a standard step angle accuracy of ±5% (non-cumulative).

Microstepping Mitigation: A 5% error on a full step could lead to minor misalignments during the scanning of 35mm or 120 film frames. To mitigate this, the system uses the Allegro A4988 stepper motor driver , which features a built-in translator supporting up to 1/16 microstepping [3]. By dividing each mechanical step into 16 microsteps, the system vastly increases linear positioning resolution and reduces mechanical vibration. This ensures the physical frame alignment tolerance remains sub-millimeter, well within the margin that the software cropping algorithms can handle.

Shaft & Load Play: The NEMA 17 motors exhibit a maximum radial play of 0.02mm and axial play of 0.08mm (at 450g load). Since the film carrier is lightweight, this mechanical play is negligible and will not negatively impact the focal plane.

Optical & Vision Tolerance

The optical system operates under strict spatial constraints, relying on a Raspberry Pi HQ Camera (IMX477), a 25mm f/1.4 CCTV lens, and a 10mm extension tube.

Working Distance & Z-Axis Tolerance: The 10mm extension tube permanently modifies the lens to shift the minimum focus distance down to a strict ~8.5cm macro working distance. At this magnification (0.42x) and a stopped-down aperture of f/5.6-f/8, the Depth of Field (DoF) is extremely narrow (only a few millimeters).

Film Flatness Tolerance: Because of the narrow DoF, the system has a very low tolerance for film curvature. The physical film carrier must hold the 35mm/120 negatives perfectly flat; otherwise, the edges of the film will fall outside the focal plane, causing blurry scans.

Sensor Resolution Tolerance: The Sony IMX477 sensor features 1.55µm pixels. This high pixel density means the system is highly sensitive to motion blur. The automated motors must come to a complete stop, and vibrations must fully dampen before the STM32 triggers the image capture.

Electrical & Power Tolerance

The system utilizes a 3S Li-Po battery (approx. 11.1V - 12V) that must power high-draw motors and sensitive logic boards simultaneously without causing voltage drops.

Stepper Driver Margins: The A4988 driver requires a load supply voltage (VBB) between 8V and 35V. The 12V battery falls comfortably within this range, providing a wide tolerance for battery voltage sag as it discharges.

Logic Voltage Stability: The A4988 logic supply (VDD) operates between 3.0V and 5.5V. The STM32 outputs a 3.3V logic signal, which perfectly aligns with this tolerance. To protect against logic-level voltage fluctuations caused by motor current spikes, the system uses an AMS1117 linear voltage regulator paired with 1µF and 4.7µF decoupling capacitors. This ensures the 3.3V rail remains strictly within the operating tolerance of the MCU and sensor logic, preventing system resets during motor actuation.

Thermal Tolerance: The A4988 drivers feature internal thermal shutdown circuitry (triggering at ~165◦C) and overcurrent protection (threshold at 2.1A). Since the motors will only drive a lightweight film carrier, the current draw will remain well below the 2A maximum, ensuring the drivers operate within safe thermal limits even inside the enclosed chamber.

3. Cost and Schedule

3.1 Cost Analysis

Item	Quantity	Unit Cost ($)	Total Cost ($)	Source
Power & Control Subsystem				
12V 2400mAh AA NI-MH Battery	1	0.17	0.17	ECE Supply Center
SPST 20A On-Off Toggle Switch	1	4.27	4.27	ECE Supply Center
PCB Mount Fuse Holder 5x20mm	1	0.80	0.80	ECE Supply Center
IRF520 MOSFET N-Channel	1	3.00	3.00	ECE Supply Center
10K Ohm 10 Watt Resistor	1	0.75	0.75	ECE Supply Center
DFR0379 Voltage Regulator 20W	1	4.90	4.90	Online Purchase
AMS1117 Linear Voltage Regulator	1	0.12	0.12	Online Purchase
SWD 0.05" 10-Pin SMT Box Header	1	1.50	1.50	Online Purchase
Capacitors (1µF, 4.7µF, 3.3pF)	1 ea.	Var.	0.35	Online Purchase
Motion & Automation				
NEMA 17 Stepper Motor	2	4.43	8.86	Online Purchase
Allegro A4988 Stepper Driver	2	6.95	13.90	Online Purchase
Illumination System				
High-CRI LED Strip	1	14.99	14.99	Online Purchase
High-CRI LED Plate	1	12.99	12.99	Online Purchase

Optical & Vision System				
Raspberry Pi HQ Camera (12MP)	1	55.00	55.00	Online Purchase
Fujian 25mm f/1.4 C-Mount Lens	1	19.54	19.54	Online Purchase
25mm 5mm Extension Tube	2	4.99	9.98	Online Purchase
15CM FFC Cable	1	6.99	6.99	Online Purchase
Total Estimated Cost			**$158.11**	

2. Cost Analysis and Budget Justification

The total projected cost for the prototype is **$158.11**, which exceeds our group's strict $150.00 budget by **$8.11** (a 5.4% variance). Despite this slight overage, the budget has been allocated as efficiently as possible without compromising the core functionality of the digitization system. The expenses are strictly necessary and justified by the following technical requirements:

2.1 The Optical System ($84.52 - The Primary Cost Driver) The vision subsystem consumes over half of the budget, but it is the most critical element of a film digitizer. Standard cheap webcams lack the dynamic range to scan film and cannot accept interchangeable lenses.

- We selected the **Raspberry Pi High Quality Camera ($55.00)** because its 12.3MP IMX477 sensor features large 1.55µm pixels and native C-Mount integration, providing the RAW fidelity required for high-quality negative inversion.
- The **Fujian 25mm Lens ($19.54)** and **Extension Tubes ($9.98)** are physically required to shift the lens's native focal length down to an 8.5cm macro working distance. This combination mathematically achieves the 0.42x magnification necessary to capture the film frame while keeping the device's physical footprint compact. Downgrading these parts would result in the device failing to physically focus on the film.

2.2 Dual-Mode Illumination ($27.98) Digitizing both transmissive film (negatives) and reflective media (Instax) requires two distinct light sources. We allocated funds for a dedicated LED Plate for backlighting and an LED Strip for angled front-lighting. Spending this money is necessary because low-quality lighting causes severe color shifts during the inversion process that the cloud software algorithms cannot fix.

2.3 Motion & Power Control ($32.88) To achieve the goal of a fast, automated system, the project requires mechanical feeding. The two **NEMA 17 Stepper Motors ($8.86)** and their corresponding **A4988 microstepping drivers ($13.90)** allow the STM32 to automatically and precisely align frames. Cutting these would force the user to manually push film through the device, defeating the project's automation value proposition.

2.4 Fiscal Responsibility and Mitigation To offset the high cost of the optical components, we heavily leveraged the ECE Supply Center for basic electronics. For example, we procured the main power source (the 12V 2400mAh battery) for only $0.17, and acquired necessary logic-level components (MOSFETs, resistors, switches, and a DFR0379 Voltage regulator for isolated power rails) for under $15 combined.

Conclusion: The $8.11 budget overage is a calculated and necessary investment. It ensures we have the specific macro-optics and automated motion drivers required to successfully build a working, high-fidelity film digitization prototype rather than a non-functional proof-of-concept.

3.2 Schedule

Week	Academic Deadline	Hardware (HW)	Firmware & Mech (FW)	Software (SW)
2/9	Proposals Due	Finalize component selection (STM32, A4988, 12V battery). Order initial breakout boards.	Define motor torque/speed needs. Draft STM32 pinout.	Define Pi 4 to STM32 UART protocol. Setup AWS/GCP cloud environment.
2/16	PCB Review & Team Contract	Complete KiCad Schematics. Start PCB Layout (Ensure 3.3pF 0201 caps and A4988 thermal vias are correct).	Setup STM32 base project. Test A4988 & motor on a breadboard with a Nucleo board.	Setup Raspberry Pi 4 OS. Test camera module using rpicam-hello.

2/23	Design Doc Due & 1st PCB Order Due	Submit 1st Round PCBway Order. Finish PCB layout (No-Fill zone for antenna, Ground planes).	Write STM32 PWM logic for LED dimming & Step/Dir logic for A4988.	Write Python script on Pi to send UART commands to STM32.
3/2	Design Reviews & 2nd PCB Order	Prepare HW sections for Design Review. Order mechanical parts & specific lab components (screws, cables).	Prepare FW sections for Design Review. Calibrate stepper motor steps per mm.	Prepare SW sections for Design Review. Develop image inversion/cropping algorithm.
3/9	Breadboard Demo & 3rd PCB Order	Breadboard Demo: Assist team in wiring dev boards. Prepare to solder 1st PCB upon arrival.	Breadboard Demo: Demonstrate STM32 receiving UART and spinning motor/lighting LED.	Breadboard Demo: Demonstrate Pi sending UART commands and capturing an image.
3/16	Spring Break	Solder components onto the 1st round PCB (use microscope for 0201 caps).	Design and 3D print/laser cut the custom optical chamber and film holders.	Refine cloud API. Ensure processing returns image to phone in < 5 min.
3/23	4th PCB Order	Hardware testing & debugging (Check 11.1V to 5V/3.3V power rails). Submit 2nd PCB order if bugs are found.	Integrate physical hardware with the 3D printed chassis.	Integrate Pi camera capture with cloud upload pipeline.

3/30	Progress Reports	Assemble 2nd iteration PCB (if needed). Assist with full system integration.	Flash final firmware to the custom PCB. Test motor/LEDs under load.	Test full software loop: Pi triggers STM32 -> Motor moves -> Pi captures -> Cloud processes.
4/6	Progress Demo	Progress Demo: Demonstrate stable power delivery and custom PCB functionality.	Progress Demo: Demonstrate accurate film advancement and lighting control.	Progress Demo: Demonstrate end-to-end image capture and cloud inversion.
4/13	Integration & Debug	Fix any lingering electrical noise or grounding issues.	Optimize motor acceleration profiles to prevent skipped steps.	Optimize image resolution (aiming for 4K) and refine color correction.
4/20	Mock Demo & Presentation	System validation testing. Verify battery life and power limits.	Finalize mechanical enclosure. Ensure no light leaks in the optical chamber.	Edge-case testing (network drops, corrupted UART packets). Prepare presentation slides.
4/27	Final Demo & Presentation	Final Demo: Present hardware reliability and PCB design choices.	Final Demo: Present mechanical robustness and firmware logic.	Final Demo: Present software pipeline and final image quality.
5/4	Final Papers & Lab Checkout	Write hardware sections of the Final Paper. Return lab inventory.	Write firmware/mechanical sections.	Write software/system sections.

4. Ethics and Safety

4.1 Societal Impact

The resurgence of analog photography has brought the authentic aesthetic of film back into mainstream culture. However, this revival is heavily bottlenecked by the archaic and cumbersome nature of analog post-processing. For the average consumer or enthusiast, developing (washing) film and manually scanning frames using bulky, expensive equipment, or waiting days for costly lab services, creates a significant barrier to entry.

Our project aims to democratize film photography by making the digitization process completely autonomous and effortless. By eliminating the steep learning curve and heavy time investment required for traditional scanning, we empower a much wider audience to engage with analog mediums.

Specifically, this device completes the final missing link for a "Fast Film Photography Solution." By pairing instant film (such as Instax) with our portable, automated scanner, users can experience the magic of physical film while entirely bypassing the darkroom and the traditional flatbed scanner. This creates a seamless bridge between the physical and digital worlds: Instant Film + Autonomous Digitization. A user captures a physical photo, inserts it into our autonomous device, and instantly receives a high-quality, fully processed digital image ready for social media.

Ultimately, this project preserves the beloved art of analog photography by adapting it to the speed, convenience, and connectivity of modern digital life.

4.2 Engineering Standards

We plan to follow engineering standards to ensure the quality of our project and alignment with our goals.

1) IEEE 802.11 (Wi-Fi): The Raspberry Pi will utilize Wi-Fi for file transfer, so we will ensure compliance with regional spectrum regulations by using standard certified modules [5].

2) USB 2.0/3.0 Standards: The interface between the STM32 and Raspberry Pi and external connections will adhere to USB voltage and current specifications.
3) JPEG/TIFF Standards: The output files will adhere to the ISO/IEC 10918-1 (JPEG) standard to ensure compatibility with all modern viewing devices and software.

4.3 Ethical Guidelines

We follow the IEEE Code of Ethics, specifically:

1) Safety (Clause 1): We prioritize user safety in regards to the lithium battery design. [4]
2) Credit (Clause 7): We acknowledge the use of open-source libraries such as OpenCV and libcamera and will not claim them as our own work [4].
3) Ethical Concerns: Digitization allows for rapid copying of copyrighted photographs. While we cannot enforce protections against misuse, we will include notices in our documentation advising users to digitize only content that they own or have express permission to use.

4.4 Safety Concerns and Measures

Lithium Battery Safety: 3S Li-Po batteries present a fire risk if overcharged or shorted. We will integrate a battery management system into our design to monitor voltage and current, and use a dedicated fuse on the PCB power input.

Mechanical Pinch Points: The motorized X-Y stage creates pinch points that can cause harm to users. We will enclose the exposed mechanism within the housing, making sure that no moving parts are accessible during operation.

Eye Safety: High-intensity LEDs will be used to assist with the scanning process. The device is designed to be a closed optical system (also known as a light tight box), which will prevent user exposure to high intensity light.

References

[1] Raspberry Pi Ltd, "Raspberry Pi High Quality Camera Product Brief," RP-008344-DS, May 2025. [Online]. Available: https://datasheets.raspberrypi.com/camera/high-quality-camera-product-brief.pdf [Accessed: Feb. 20, 2026].

[2] STMicroelectronics, "STM32F446xC/E Datasheet," DS10693 Rev 10, 2024. [Online]. Available: https://www.st.com/resource/en/datasheet/stm32f446re.pdf [Accessed: Feb. 20, 2026].
[3] Allegro MicroSystems, "A4988 DMOS Microstepping Driver with Translator and Overcurrent Protection," Datasheet, 2020.
[4] *IEEE Code of Ethics*, IEEE, 2020. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html
[5] *FCC Rules and Regulations*, Title 47, Part 15, Federal Communications Commission.