Eco-Trim: Smart Scratch Pad Recovery System

ECE 445 Senior Design

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Abstract

Eco-Trim is a compact mechatronic system that identifies usable blank regions on partially used paper and cuts those regions away for reuse. The machine feeds sheets individually, scans surface reflectivity to detect candidate blank regions, calculates the correct blade timing from the fixed sensor-to-cutter spacing, and cuts out reusable blank paper sections. This draft reflects the current design direction by avoiding unapproved claims about fixed output size or chemical-processing comparisons.

1. Introduction

1.1 Objective and Problem Statement

Libraries, study rooms, and campus workspaces generate large amounts of paper waste from single-sided printouts, partial notes, and draft documents. Many sheets still contain usable blank areas, but manually locating and trimming those areas is inconvenient and inconsistent. Conventional shredders destroy both printed and blank regions, while ordinary disposal throws away paper that still has practical value.

Eco-Trim addresses this gap with a local automated reuse workflow. The user inserts a stack of paper, closes the enclosure, and presses one start button. The machine then separates and feeds sheets one at a time, optically scans each sheet, identifies a sufficiently large blank region, and cuts out that blank region so it can be reused.

1.2 Visual Aid

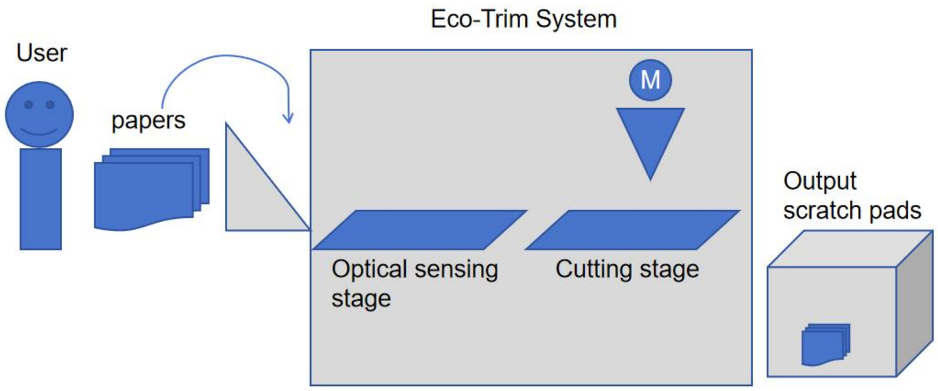

Figure 1. Rough draft concept sketch of Eco-Trim in use.

1.3 High-Level Requirements

- The feed mechanism shall process at least 5 consecutive sheets under normal operation without repeated multi-sheet feeding and without an unrecovered jam.
- The sensing and control system shall identify a continuous blank region of at least 100 mm and distinguish blank versus printed regions with a target decision accuracy of at least 95% on the team test set.
- The cutter shall separate the selected blank region with cut-position error no greater than +/-2 mm relative to the intended cut boundary, and each cut shall complete within 1.5 s.
- The enclosure interlock and IR light curtain shall physically remove motor power within 100 ms of an unsafe access event.

2. Design

2.1 Top-Level Design Description

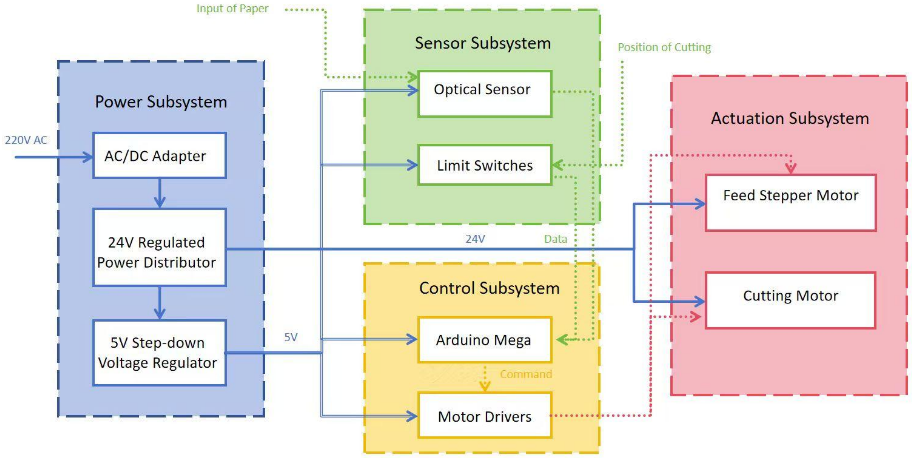

Figure 2. Top-level block diagram of Eco-Trim in use.

The proposed system integrates three primary technical subsystems - sensing, control, and actuation/safety - supported by a simple off-the-shelf power and interface architecture. The prototype does not include a custom mains or analog power design. Instead, it uses a certified external 24 V AC/DC supply, a commercial buck module to generate 5 V logic power, and module-level wiring between the controller, sensor, motor driver, and safety switches. This keeps the team-designed portion focused on mechanics, sensing, timing, and safety behavior while still documenting the power path needed for integration.

2.2 Supporting Power and Interface Architecture

This design review does not claim a custom electrical subsystem. The student-built hardware operates only from low-voltage DC: a purchased 24 V supply powers the motor path, and a commercial LM2596 buck module provides the 5 V rail for the Arduino, reflective sensor, switches, and interface electronics [1], [2]. The final design will integrate these commercial sensing and motor-driving circuits onto a custom-designed PCB shield that mounts directly onto the microcontroller. For this document, we present the functional electrical interface diagram that will dictate our custom PCB layout.

Table 1. Supporting power and interface architecture requirements and verification plan.

Requirement	Verification
External 24 V supply and distribution path shall provide 22.8 V to 25.2 V at the motor driver input under expected load.	Measure the 24 V line at the supply output and TB6600 input using a DMM while running feed and cut motions. Pass if all readings remain within range.
5 V logic rail from the buck module shall remain between 4.75 V and 5.25 V during startup and motor switching.	Probe the 5 V rail with a DMM and oscilloscope while repeatedly actuating the feed motor and cutter. Pass if both steady-state value and transient excursions remain within limits.
Emergency-stop/interlock path shall remove drive power or driver enable within 100 ms without damaging the controller.	Open the enclosure or block the IR curtain while monitoring the motor-enable line or motor supply with an oscilloscope. Pass if the driver is disabled within 100 ms and the controller can reinitialize after reset.

2.3 Sensor Subsystem

The sensing subsystem uses an E18-D80NK reflective optical sensor [7] to perform a one-dimensional scan along the feed direction. Printed regions are expected to return different reflectivity values from blank paper, allowing the controller to detect the start and length of a blank segment. The sensor should be mounted at fixed height, shielded from stray ambient light when necessary, and calibrated using labeled paper samples before final threshold selection.

Table 2. Sensor subsystem requirements and verification plan.

Requirement	Verification
Sensor shall sample reflectivity at 100 Hz or higher.	Measure the sensor acquisition rate in firmware using timestamped serial logs or timer instrumentation. Pass if the effective sampling rate is at least 100 Hz.
Sensor path shall detect a blank region of at least 100 mm with target classification accuracy of >=95%.	Prepare at least 20 labeled paper samples, measure blank-region ground truth using a ruler or calipers, and compare firmware decisions to the labeled set. Pass if at least 19 of 20 decisions are correct.
Sensor mounting shall remain aligned during repeated feeding.	Run repeated feed tests and inspect whether threshold drift is caused by mechanical movement. Pass if no re-alignment is required during the test set.

2.4 Control Subsystem

The control subsystem is centered on an Arduino Mega-class controller [1]. The controller runs the finite state machine, reads the optical sensor and safety switches, commands the feed stepper and cutter driver, and handles faults such as jams, timeout conditions, or unexpected switch responses. The most important geometric parameter is the fixed distance D from the sensor to the cutter, because that offset translates each sensing decision into a commanded feed motion.

Table 3. Control subsystem requirements and verification plan.

Requirement	Verification
Controller shall execute the main control loop fast enough to update motion and safety state deterministically.	Measure the elapsed time of one control loop over at least 100 iterations using timer instrumentation or a logic-analyzer pulse and compare the maximum loop time against the selected design limit.
Position tracking shall support cut placement within +/-2 mm.	Command multiple cuts on marked test sheets and measure actual cut locations using calipers. Pass if every sample falls within +/-2 mm.
Firmware shall enter a fault state when the expected switch event is not detected within the motion window.	Disable or block the relevant switch and command a cycle. Pass if motion halts and the controller reports a fault through the serial log instead of continuing the sequence.

2.5 Actuation and Safety Subsystems

The actuation subsystem includes the sheet-feed stepper motor, the cutter actuator, the TB6600 motor driver, limit switches, and the associated mechanical paper path [5], [6], [8], [9]. A stepper motor is preferred for feed control because it provides deterministic incremental motion. The safety subsystem spans the entire machine. The enclosure must prevent finger access to moving parts, while a hardware interlock path disconnects motor drive if the enclosure opens or the IR curtain is broken.

Table 4. Actuation and safety requirements and verification plan.

Requirement	Verification
Feed subsystem shall process 5 consecutive sheets without repeated multi-feed or unrecovered jam.	Perform repeated five-sheet trials with representative office paper and record every feed event using a test log. Pass if the system completes the run with single-sheet behavior and no manual jam recovery.
Cutter shall complete one cut in <=1.5 s and produce no visible tear longer than 3 mm.	Measure cut time using a stopwatch or high-frame-rate video and inspect edge quality with a ruler or calipers. Pass if all samples meet both time and edge requirements.
Interlock and IR curtain shall remove motor power within 100 ms.	Monitor motor-enable or supply lines with an oscilloscope while opening the enclosure or blocking the curtain. Pass if power removal occurs within 100 ms.

2.6 Software Flow

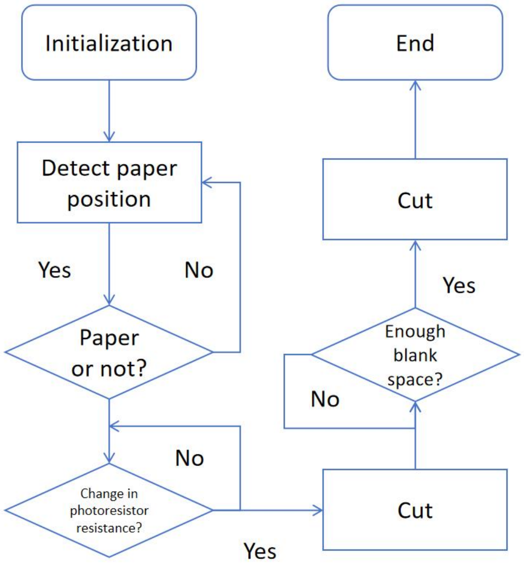

Figure 3. Software flow of Eco-Trim in use.

The first hardware figure in this section is intentionally a top-level block diagram rather than a component-level electrical schematic. Since the prototype currently uses commercial modules instead of a custom PCB, the final electrical package for the course will be a wiring and interconnection schematic that labels Arduino I/O pins, TB6600 control signals, sensor input, switch inputs, common ground, nominal 24 V / 5 V rails, and the hardware interlock path. The firmware should be implemented as a finite state machine with at least the following states: Idle, Initialize, Load Sheet, Scan Sheet, Validate Blank Region, Advance to Cut Position, Execute Cut, Output, Fault, and Emergency Stop.

2.7 Preliminary Calculations and Numerical Feasibility Check

The feed-positioning design can be justified with a simple kinematic calculation. For a feed roller radius r = 15 mm and a full-step angle theta = 1.8 deg = pi/100 rad, the nominal paper travel per full step is s_step = r * theta = 15 * pi / 100 = 0.471 mm/step.

For a target travel distance L = 100 mm from the sensed boundary to the intended cut line, the required number of full steps is N = L / s_step = 100 / 0.471 = 212.3 steps. Rounding to the nearest full step gives a quantization error bounded by dx_step <= s_step / 2 = 0.236 mm.

The sensor sampling rate also constrains boundary localization. If the scan speed is limited to v_scan = 50 mm/s and the sampling rate is f_s = 100 Hz, then the spatial sample spacing is dx_sample = v_scan / f_s = 0.50 mm/sample. A 100 mm blank region therefore spans about 200 samples, which is sufficient for robust detection on the prototype.

Section 4 uses these values together with conservative radius and slip bounds to perform a worst-case numerical tolerance check. The calculation supports the feasibility of step-count-based positioning for the initial prototype.

3. Requirements and Verifications

Table 5. Consolidated system requirements and verification matrix.

Requirement	Verification
System shall feed at least 5 individual sheets continuously under normal operation.	Run a five-sheet continuous feed test using representative paper. Record feed count, repeat-feed events, and jams with a test log or video. Pass if all five sheets complete without repeated multi-feed and without manual recovery.
System shall detect a >=100 mm blank region and make the correct cut/no-cut decision with >=95% accuracy on the team test set.	Use a labeled set of printed and blank patterns, measure the blank-region ground truth with a ruler or calipers, and compare firmware decisions to the known ground truth. Pass if the system reaches at least 95% correct decisions.
Cut-boundary error shall be no more than +/-2 mm.	Measure intended versus actual cut location on marked sheets using calipers. Pass if every sample is within the allowed error band.
Each cut shall complete in <=1.5 s.	Trigger cuts repeatedly and measure the elapsed time using a stopwatch or high-frame-rate video. Pass if every cut is within the specified time.
Hardware safety interlock shall remove motor power in <=100 ms.	Observe motor power or enable signals on an oscilloscope during unsafe-access events. Pass if shutdown occurs in 100 ms or less.

4. Tolerance Analysis

The dominant tolerance issue in Eco-Trim is the positional uncertainty between optical detection and the cut location. The cut-position error budget can be modeled as dx_total = dx_sensor + dx_step + dx_radius + dx_slip, where the terms represent sensing resolution, step quantization, roller-radius error, and paper slip, respectively.

Using conservative bounds for a 100 mm commanded travel gives: dx_sensor <= 0.50 mm from the 100 Hz sampling limit at 50 mm/s, dx_step <= 0.236 mm from full-step quantization, dx_radius <= L * (dr / r) = 100 * (0.10 / 15) = 0.67 mm for a radius tolerance dr = +/-0.10 mm, and dx_slip <= 0.50 mm for 0.5% slip over 100 mm of travel.

The worst-case linear stack-up is therefore dx_total <= 0.50 + 0.236 + 0.67 + 0.50 = 1.91 mm, which remains inside the +/-2 mm cut-placement requirement. A root-sum-square estimate gives approximately 1.00 mm, providing additional design margin under normal operation.

To preserve this margin in practice, the team should use a high-friction roller surface, maintain controlled pinch pressure, calibrate true travel per motor step experimentally, and repeat 100 mm feed trials to confirm that slip and radius error stay within the assumed bounds.

5. Cost Analysis

5.1 Bill of Materials

Table 6. Prototype bill of materials (materials only, RMB).

Item	Part / Assembly	Module	Unit Price (RMB)	Qty	Subtotal (RMB)
1	Arduino Mega 2560 compatible board	Control	69	1	69
2	E18-D80NK reflective sensor	Sensor	14.63	1	14.63
3	42 stepper motor	Actuation	36	1	36
4	TB6600 driver	Actuation	20	1	20
5	24 V / 5 A power supply	Power	106.16	1	106.16
6	LM2596 buck converter	Power	2.5	1	2.5
7	Limit switches	Safety	5.6	2	11.2
8	IR safety curtain / light grid	Safety	218	1	218
9	M3 screw assortment	Mechanical / System	15	1	15
10	M3 nuts and washers	Mechanical / System	8	1	8
11	Brass standoffs	Mechanical / System	12	1	12
12	PLA filament for 3D printing	Mechanical / Enclosure	25	1	25
13	Perfboard / prototyping materials	Integration	50	1	50
14	Frame, wiring, connectors, heat-shrink	Mechanical / System	85	1	85

Material pricing in Table 6 is based on representative component sources [7]-[10] and local hardware estimates. Because the prototype relies on purchased modules rather than a custom PCB, the electrical-material cost is limited to the external supply, buck module, driver, switches, wiring, and perfboard.

Estimated material subtotal: RMB 677.49.

Estimated external fabrication or shop-support reserve: RMB 100.

5.2 Labor and External Fabrication

The out-of-pocket prototype budget is not the same as the full project cost for design-document accounting. To reflect engineering effort, this document includes an equivalent student labor estimate together with a small reserve for outside fabrication or shop support.

Table 10. Labor and non-material cost estimate.

Category	Basis	Cost
Equivalent student engineering labor	4 members × 30 h/member × RMB 50/h	RMB 6000.00
External fabrication / shop-support reserve	3D-print rework, minor machining, or emergency replacement parts	RMB 300.00
Total project cost including labor	Material + labor + reserve	RMB 6977.49

Estimated total prototype budget: RMB 6977.49.

6. Schedule

Table 7. Updated week-by-week implementation plan.

Week	Specific engineering task	Deliverable	Assigned member(s)
Week of Apr 6	Freeze subsystem interfaces, revise document language, and finalize the first procurement list.	Updated design document and procurement list.	All members
Week of Apr 13	Finalize the wiring/interconnect diagram and bench-test the external 24 V supply, buck module, and emergency-stop path.	Wiring/interconnect diagram and power-path test data.	Zhizheng Ju, Tianyi Xu
Week of Apr 20	Assemble the feed path, mount the optical sensor, and characterize sensor response on representative paper.	Sensor threshold dataset and mechanical alignment notes.	Lehan Pan, Zihan Wang
Week of Apr 27	Integrate the feed motor, cutter, switches, interlock path, and control firmware into a working prototype.	Integrated prototype ready for debugging.	All members
Week of May 4	Have a working prototype available and begin requirement-verification	Prototype milestone and first R&V results.	All members

	and bug-fix cycles.		
Week of May 11	Finish major bug fixes, complete remaining R&V tests, and prepare demo flow and presentation materials.	Stable demo build and supporting test data.	All members
Week of May 18	Perform the final demo, presentation, and submission cleanup.	Final demonstration package.	All members

7. Ethics and Safety

Eco-Trim should be presented in a way consistent with the ACM Code of Ethics and Professional Conduct and the IEEE Code of Ethics [3], [4]. In practice, this means the team should report only measured performance, avoid exaggerated sustainability claims, and communicate known failure modes honestly. The machine does not create new paper; it only recovers usable blank areas from partially used sheets, so any claims about waste reduction, throughput, detection accuracy, or cut precision must be backed by test data.

The same ethics principles also apply to user privacy. Because the device processes partially printed documents, the design should minimize unnecessary retention of printed content. The sensor is used only for reflectivity-based blank detection rather than document imaging, and any temporary debugging data should be discarded once thresholds and control logic are validated.

The main safety hazards are the blade, the roller pinch points, and unexpected motor motion. These hazards justify an enclosure, a lid interlock, and an IR light curtain that remove motor drive through a hardware path rather than firmware alone. During testing, the team should keep hands out of the paper path, wear eye protection when the cutter is energized, and de-energize the mechanism before adjustments or jam clearing.

Electrical safety should also be treated conservatively. The prototype should use a certified external 24 V AC/DC power supply so that 220 V AC remains confined to the purchased adapter rather than the student-built enclosure. Inside the prototype, only low-voltage DC should be distributed. Wiring should be strain-relieved and insulated, and any verification involving live power should follow applicable lab or machine-shop safety procedures.

8. References

[1] Arduino, "Mega 2560 Rev3," Arduino documentation.
[2] Texas Instruments, "LM2596 SIMPLE SWITCHER Power Converter 150-kHz 3-A Step-Down Voltage Regulator," datasheet.
[3] Association for Computing Machinery, "ACM Code of Ethics and Professional Conduct," 2018.
[4] IEEE, "IEEE Code of Ethics."
[5] OpenBuilds, "Introduction to Stepper Motors and Motion Control," reference article.
[6] Omron, "General-Purpose Basic Switches," datasheet family.
[7] Representative marketplace listing, "E18-D80NK reflective photoelectric sensor."
[8] Representative marketplace listing, "TB6600 stepper motor driver."
[9] Representative marketplace listing, "42 stepper motor."
[10] Representative marketplace listing, "24 V switching power supply."