

MaterialID: Multi-Modal Material Identification System

ECE 445 Design Document - Team 47

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Abstract

This document presents the detailed design of MaterialID, a bench-top instrument that identifies a constrained set of engineering materials by combining eddy-current sensing, dielectric sensing, and mechanical damping measurements. The design uses a custom two-layer PCB centered on an STM32G474RET6 microcontroller, a programmable excitation path, analog front ends for the electrical sensors, a solenoid-driven mechanical impulse subsystem, an OLED user interface, and USB/SWD debugging interfaces. The document expands the approved proposal into implementation level subsystem descriptions, quantitative requirements and verification procedures, a physical and PCB design, tolerance analysis, cost analysis, project schedule, and safety/ethics plan.

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1. Introduction

1.1 Problem

Machine shops, makerspaces, teaching laboratories, and manufacturing facilities frequently accumulate leftover pieces of raw material whose original labels or markings have been removed. Once these markings are lost, visually identifying the material can become difficult because many common engineering materials have similar appearances.

Incorrect identification can lead to inappropriate machining parameters, joining processes, or handling procedures. Metals that appear visually similar can have very different electrical conductivity, magnetic behavior, strength, corrosion resistance, and machinability [8], while plastics can appear nearly identical despite different mechanical and thermal properties. Unidentified stock may therefore be processed incorrectly or discarded entirely.

Existing low-cost identification methods usually measure only one physical property. A magnet can separate many ferromagnetic materials from non-ferromagnetic materials, but provides little information about aluminum, copper, brass, or plastics. Electrical conductivity measurements distinguish conductors but do not identify nonconductors, while visual inspection depends strongly on surface finish and operator experience. X-ray fluorescence instruments can identify elemental composition, but are substantially more expensive and more capable than is necessary for a teaching laboratory or small machine shop. MaterialID addresses this gap with a lower-cost instrument that combines multiple independent physical measurements.

1.2 Solution

MaterialID identifies an unknown sample by combining electromagnetic, dielectric, and mechanical information. The user places a flat sample on the sensing platform and presses a measurement button. The device first excites an eddy-current coil at multiple frequencies and measures the magnitude and phase response. Conductive samples alter the effective coil impedance according to conductivity and magnetic permeability. If the sample does not produce a significant eddy-current response, the system uses a PCB-based fringing-field capacitive sensor to measure dielectric response. A third measurement is obtained by applying a controlled impulse with a 12 V solenoid and recording the resulting vibration or acoustic ring-down. The STM32G474RET6 coordinates the excitation, sensor selection, ADC acquisition, mechanical impulse, feature extraction, classification, OLED display, and USB debugging. The classifier compares measured features with a calibrated reference table and displays a predicted material and confidence value. Measurements that do not match a calibrated class sufficiently closely return UNKNOWN instead of forcing a classification. The required material classes are 6061-T6 aluminum, C110 copper, C360 brass, 1018 mild steel, cast acrylic (PMMA), and HDPE. Specific grades are used because electrical conductivity can vary substantially within a metal family; this prevents the project from making unsupported claims about arbitrary aluminum or brass alloys.

1.3 Visual Aid

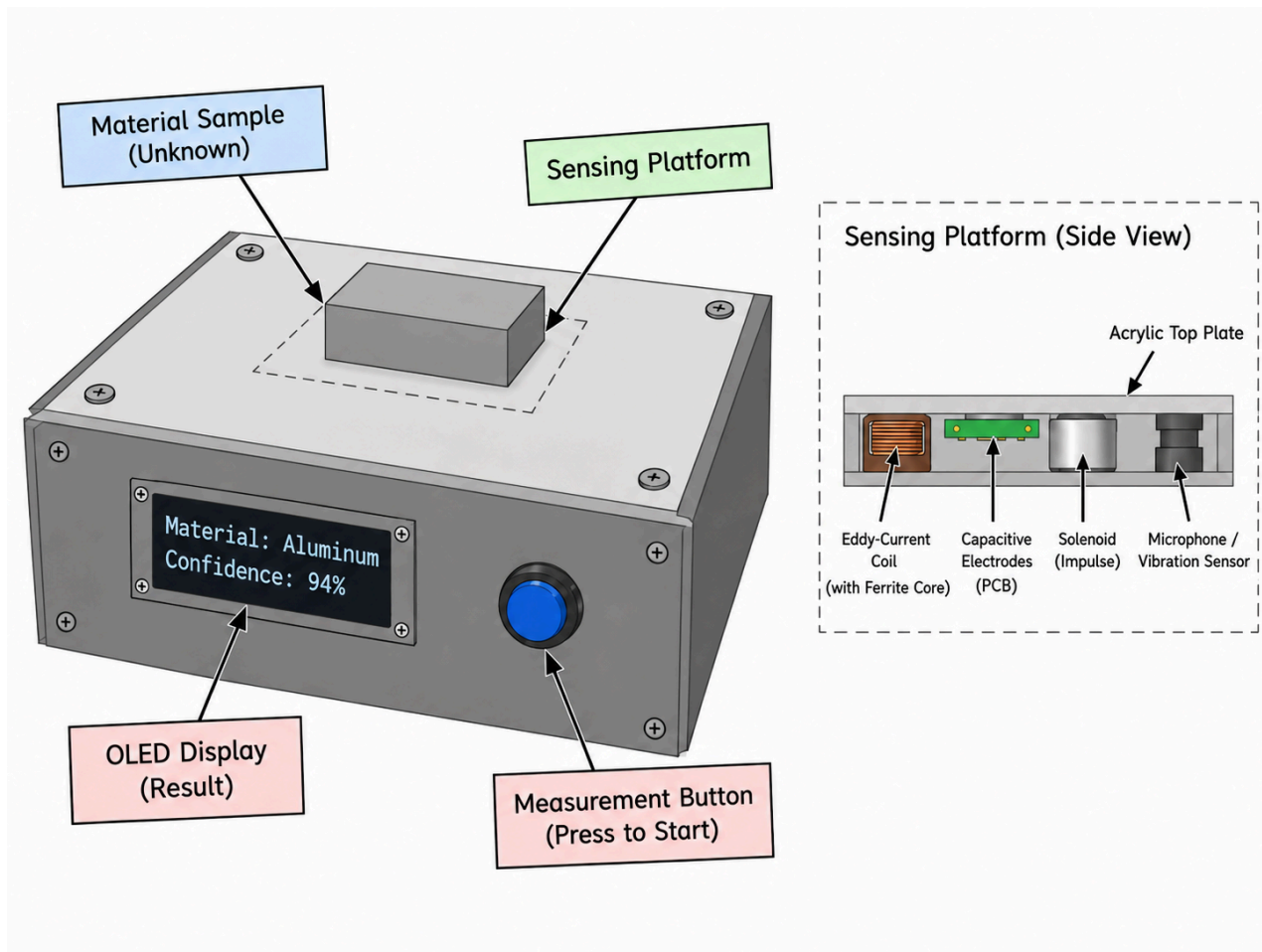


Figure 1. Intended use of MaterialID and conceptual sensing-platform arrangement (from the approved proposal).

The user interaction is intentionally simple: place the material sample on the top sensing area, press the measurement button, and read the material prediction and confidence on the OLED. The side view indicates the intended co-location of the eddy-current coil, capacitive electrodes, solenoid, and vibration sensor beneath the sensing surface.

1.4 High-Level Requirements (HLRs)

- The system shall correctly identify at least 90% of 60 controlled material-identification trials across the six required material classes, with at least one physical sample of each material excluded from the reference-calibration data.
- Ten repeated identifications of the same physical sample, with the sample removed and re-placed between trials, shall return the same displayed material in at least 9 of the 10 trials.
- The system shall complete the full measurement, classification, and display sequence within 5 seconds of the user pressing the measurement button without requiring the user to enter the expected material type or sample dimensions, provided the sample is at least 3 mm thick and fully covers the sensing area.

2. Design

2.1 Block Diagram

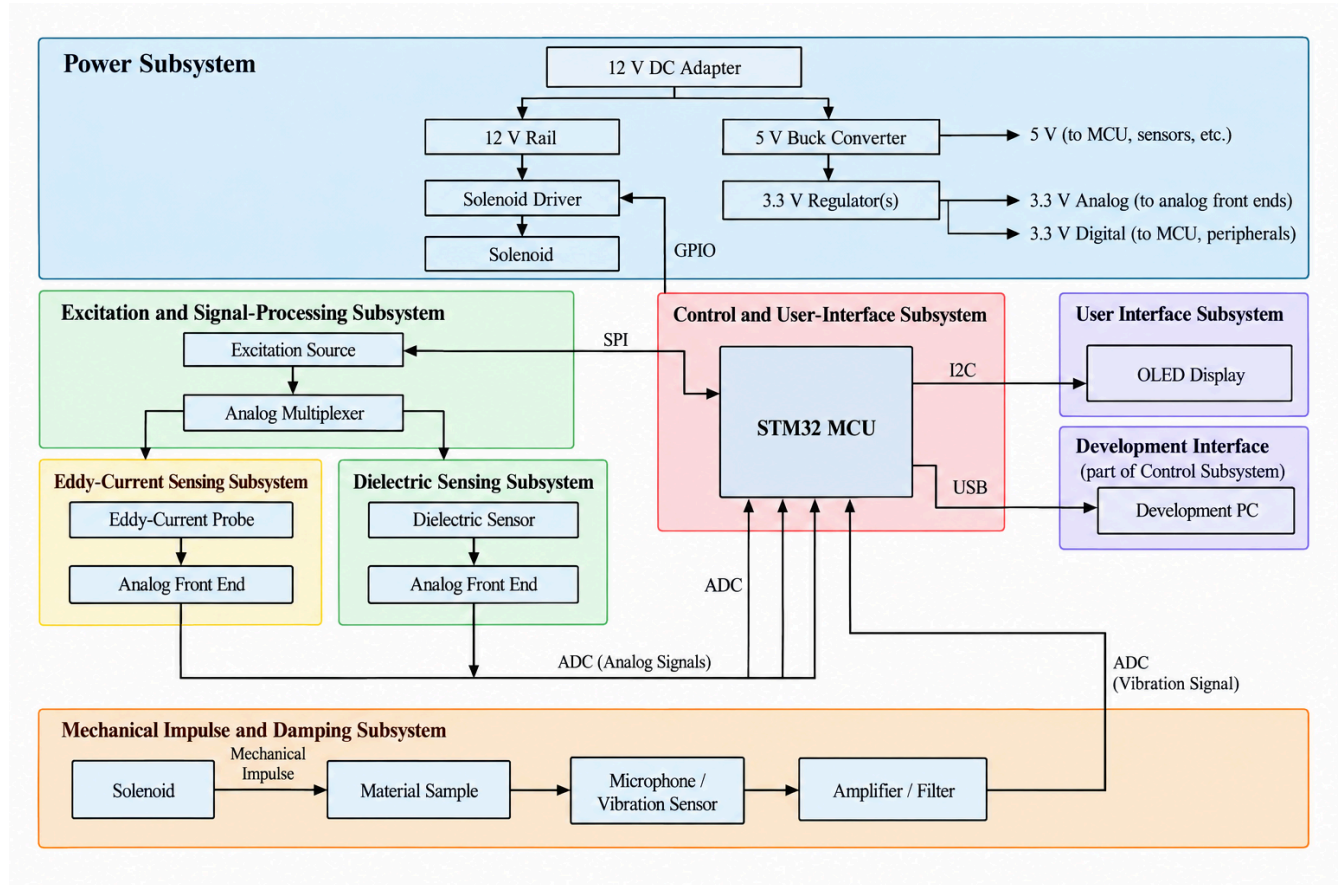


Figure 2. MaterialID system block diagram.

The system is divided into six modular subsystems: excitation and signal processing, eddy-current sensing, dielectric sensing, mechanical impulse and damping, control/user interface, and power. The 12 V adapter directly supplies the solenoid branch and feeds a 5 V regulator. Separate 3.3 V analog and digital rails are derived from 5 V. The STM32 configures the AD9833 excitation source over SPI, selects the excitation path, acquires analog signals through its ADCs, controls the solenoid through a GPIO-driven MOSFET, drives the OLED through I2C, and exposes USB and SWD interfaces for calibration and debugging.

2.2 Physical and PCB Design

The physical implementation is a bench-top instrument with a sensing platform above the sensor electronics. The sample rests on an insulating top surface and must fully cover the active sensor region. A ferrite-backed eddy-current coil and the fringing-field dielectric electrodes are positioned immediately below the top surface to maximize electrical coupling. The solenoid is placed beneath the sample so its plunger can deliver a repeatable impulse, while a piezoelectric or MEMS vibration sensor is mechanically coupled to capture the transient ring-down. The actuator is enclosed so that a user cannot contact the moving mechanism during normal operation. A temperature sensor is mounted next to the eddy-current coil so the controller can detect baseline drift.

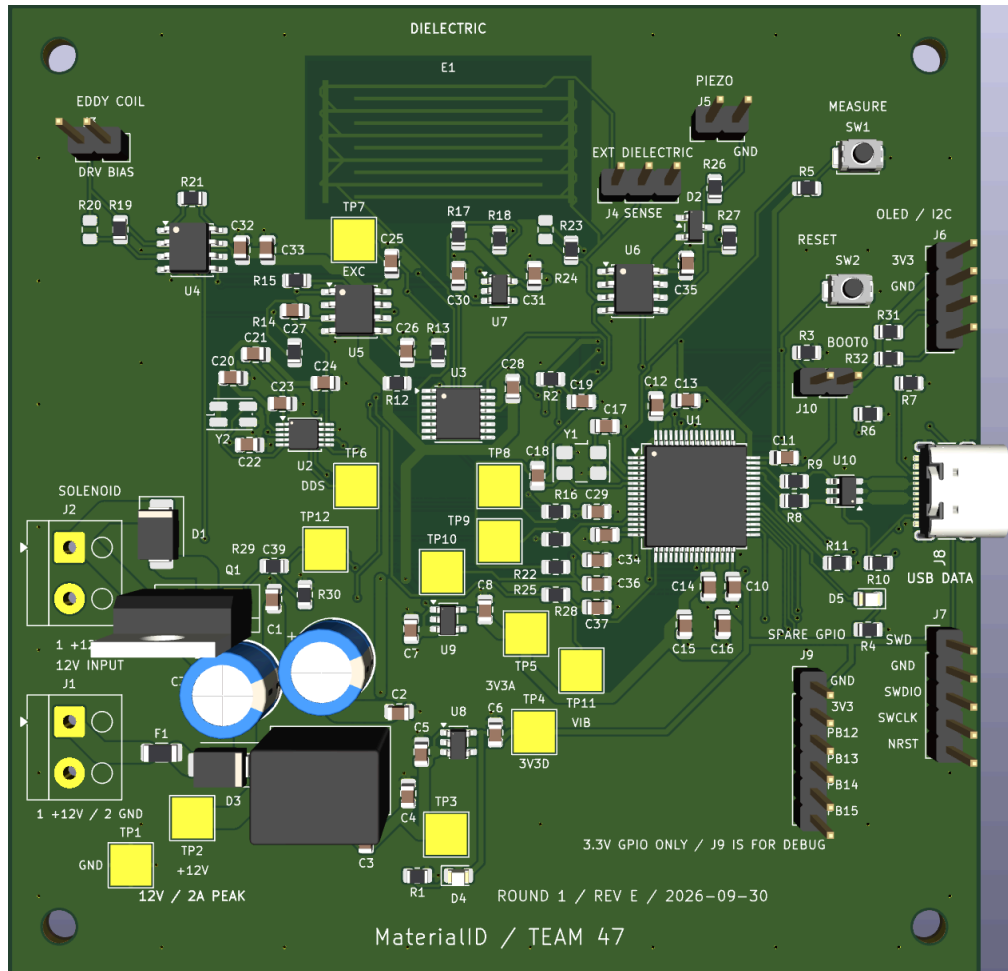


Figure 3. Current MaterialID KiCad PCB floorplan/placement snapshot

The controller/sensing PCB is approximately 95 mm x 95 mm, keeping it within the ECE 445 100 mm x 100 mm fabrication limit. Four M3 mounting holes are located near the corners. Connectors are placed near board edges for the 12 V input, solenoid, eddy-current coil, dielectric sensor, vibration sensor, OLED, SWD, and USB interfaces. The floorplan separates a quiet analog/sensor region from the MCU/digital region and the high-current power/solenoid region. Eleven test points expose GND, 12 V, 5 V, 3.3 V digital, 3.3 V analog, DDS raw output, excitation buffer output, and all four ADC measurement nodes to simplify bring-up and debugging.

The routing plan follows the course PCB review guidance: ordinary signals use approximately 0.25 mm traces, MCU power uses approximately 0.5 mm traces, and higher-current power paths use wider traces as appropriate. A continuous ground plane will be maintained wherever possible. USB D+ and D- will be routed as a short, length-matched differential pair with an uninterrupted ground reference and geometry selected for approximately 90 ohm differential impedance. Decoupling capacitors are placed close to each IC supply pin, the STM32 crystal is placed close to the oscillator pins, and the solenoid switching loop is kept compact and physically separated from sensitive analog paths.

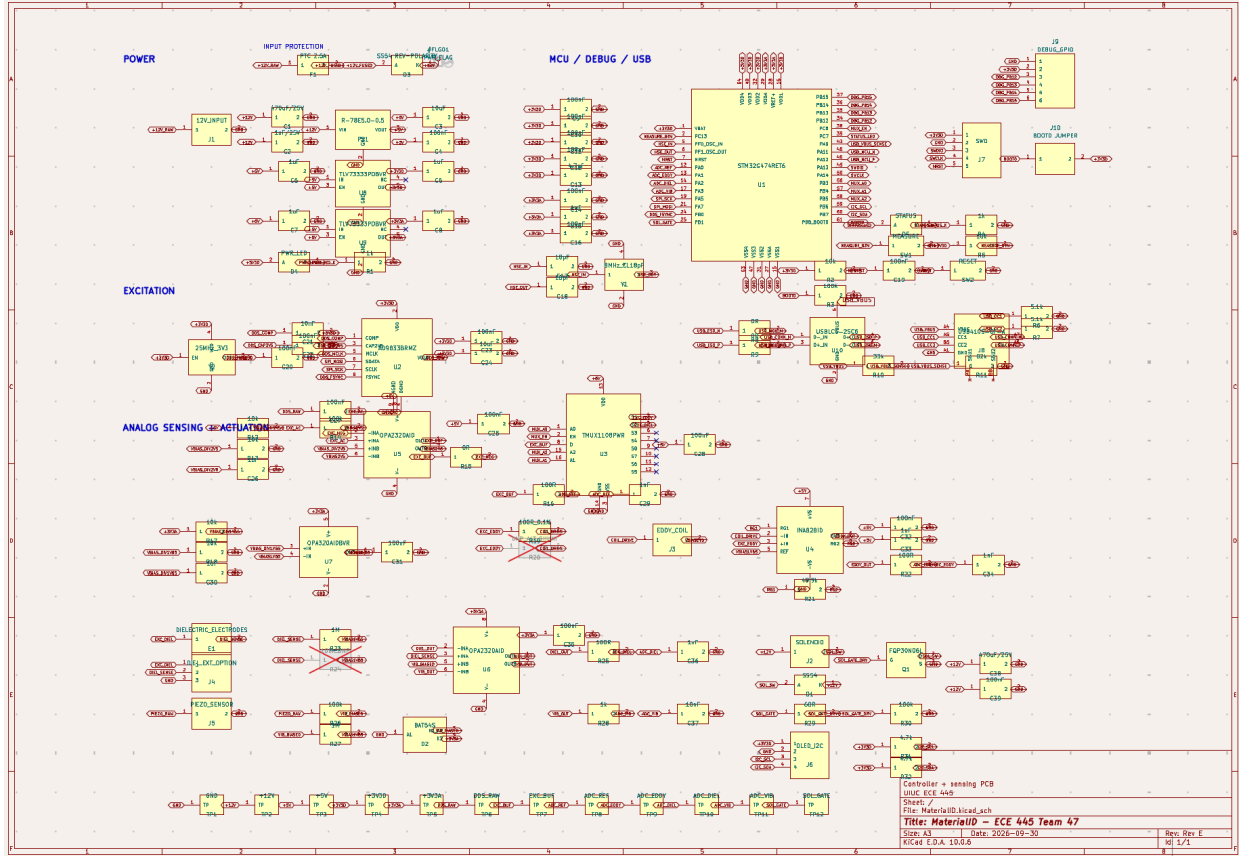


Figure 4. Current MaterialID controller and sensing schematic in KiCad. The design includes power conversion, STM32 control/debug, DDS excitation, muxing, three analog measurement paths, solenoid drive, and test points.

Figure 4 shows the detailed implementation used to create the current PCB. Major components include the STM32G474RET6 (U1), AD9833BRMZ DDS (U2), TMUX1108PWR multiplexer (U3), INA828 instrumentation amplifier (U4), OPA2320/OPA320 analog stages (U5-U7), TLV73333 regulators for separate analog/digital 3.3 V rails (U8-U9), USBLC6-2SC6 USB protection (U10), an R-78E5.0-0.5 5V regulator (PS1), FQP30N06L solenoid MOSFET (Q1), SS54 protection diodes, an 8 MHz MCU crystal, and a 25 MHz DDS oscillator. The analog outputs are brought to ADC_REF, ADC_EDDY, ADC_DIEL, and ADC_VIB test points and MCU ADC channels.

2.3 Excitation and Signal-Processing Subsystem

This subsystem creates the repeatable electrical stimulus required by both electrical sensing modes and extracts magnitude/phase information used by the classifier. It directly supports HLRs 1 and 2 because classification and repeatability depend on stable excitation and accurate phase/magnitude measurement; its acquisition time also contributes to the 5 s limit in HLR 3.

The AD9833BRMZ is clocked from a 25 MHz oscillator and configured by the STM32 over SPI [3]. Firmware selects 60 kHz or 240 kHz sine excitation. The DDS output is buffered before the TMUX1108. The multiplexer is intentionally placed on the excitation side rather than directly on the high-impedance dielectric sensing node because the TMUX1108 [10] common-node off capacitance is large enough to load the capacitive sensor. The MCU acquires a reference copy of the excitation and the conditioned sensor response so synchronous detection can compute in-phase and quadrature components, then convert them to magnitude and phase. At 240 kHz, 1° of skew is about 11.6 ns, so the reference and response channels are sampled simultaneously by ADC1 and ADC2 in dual

simultaneous mode, which removes skew rather than compensating for it.

For a sampled waveform $x[n]$ of N samples with sampling period T_s and a reference at angular frequency $\omega = 2\pi f$, firmware estimates the in-phase (I) and quadrature (Q) terms, magnitude (M), and phase (ϕ) as follows:

$$I = (2/N) \sum x[n] \cos(\omega n T_s), \text{ sum over } n = 0 \text{ to } N - 1$$

$$Q = - (2/N) \sum x[n] \sin(\omega n T_s), \text{ sum over } n = 0 \text{ to } N - 1$$

$$M = \sqrt{I^2 + Q^2}; \phi = \text{atan2}(Q, I)$$

Applied to the reference and sensor channels, their relative M and ϕ become the baseline-subtracted classifier features. The primary feature of a channel is the baseline-subtracted M or ϕ , at 60 kHz or 240 kHz, that gives the largest separation for the pair or sample under test.

Requirement	Verification
The buffered excitation delivered to the sensor path shall have its second and third harmonics at least 40 dB below the fundamental at both 60 kHz and 240 kHz.	Capture the buffer output at the sensor connector with the ADC or an oscilloscope FFT at each frequency, and compute the harmonic-to-fundamental ratios. Both must be at least 40 dB.
Drive amplitude shall match between the two excitation frequencies within +/-5% and remain stable within +/-2% during any 5 s measurement.	Measure peak-to-peak excitation amplitude at 60 kHz and 240 kHz with an oscilloscope under representative sensor loads. Log amplitude at the beginning and end of a 5 s sequence and compare the two frequency settings.
Reference and response channels shall be sampled with effective inter-channel skew <=1 degree at 240 kHz and at least 8 samples per excitation period.	Feed the same sinusoid to both acquisition paths, record raw ADC samples, and estimate the measured phase difference. Verify ADC sample rate from firmware timer configuration and captured timestamps.
Synchronous detection shall recover magnitude within +/-1% and phase within +/-1 degree of a known RC reference at both frequencies.	Connect RC network with analytically calculated transfer magnitude/phase. Record ADC data, run the firmware detector, and compare calculated and measured values at 60 and 240 kHz.
Firmware sensor-path selection shall settle within 10 ms and attenuate the unselected path by at least 40 dB.	Toggle TMUX1108 selection while observing the selected and unselected outputs on two oscilloscope channels. Measure settling time and $20\log_{10}(V_{\text{unselected}}/V_{\text{selected}})$.
Reference and response signals at the STM32 ADC pins shall remain between 0.1 V and 3.2 V for all required materials and the empty-platform condition.	Probe ADC_REF and the active response ADC node while testing all six materials and no sample. Record minimum/maximum voltage and verify no clipping or rail contact.

Table 1. Excitation and signal-processing subsystem requirements and verifications

2.4 Eddy-Current Sensing Subsystem

The eddy-current subsystem is the primary sensing path for 6061-T6 aluminum, C110 copper, C360 brass, and 1018 mild steel. A ferrite-backed coil creates an alternating magnetic field, and eddy currents in a conductive sample alter the coil impedance according to conductivity and magnetic permeability. Measuring at 60 kHz and 240 kHz gives a multidimensional feature vector instead of a single scalar. The INA828 instrumentation amplifier runs from the 5 V rail because its minimum single-supply voltage is 4.5 V [4], and its output is scaled so the STM32 ADC sees 0.1-3.2 V. The coil connects through J3 so its geometry can change during characterization without respinning the PCB, and the ADC_EDDY and ADC_REF test points allow measurement independent of firmware. This subsystem directly supports HLR 1 because its 60 kHz and 240 kHz features separate aluminum, copper, brass, and mild steel, and HLR 2 because baseline subtraction and the $\pm 10\%$ repeatability requirement keep repeated placements within the same feature region.

Requirement	Verification
At 60 kHz, the primary feature measured on a 3 mm thick aluminum or brass coupon shall be within 2% of the feature measured on a 10 mm coupon of the same material.	Place 3 mm and 10 mm aluminum and brass coupons 10 times each, compute the mean feature values, and verify the difference is at most 2% for each metal.
Relative to the empty-platform baseline, the primary feature change shall be ≥ 10 times baseline standard deviation for each conductive material and ≤ 3 times for acrylic and HDPE.	Collect at least 20 empty-platform readings to estimate baseline mean and standard deviation, then 10 readings for each material. Compute $ \text{feature-material} - \text{baseline} / \text{sigma_baseline}$.
For each of the six conductive-material pairs, at least one primary feature shall differ by ≥ 6 pooled standard deviations over ten trials.	Collect 10 removed/replaced trials per conductor, compute each pair's separation in pooled standard deviations, and confirm every pair has a feature at $\geq 6\sigma$.
Ten measurements of the same sample, removed and re-placed between trials, shall produce each primary feature within $\pm 10\%$ of the mean.	Perform ten independent placements of each representative conductive coupon. Compute feature mean and percent deviation for each trial.
The device shall acquire an empty-platform baseline at power-up and on user request, and shall prompt for re-baseline when the coil temperature has changed by 0.3°C or more since the last baseline.	Power cycle to confirm automatic baseline. Heat and cool the coil while logging temperature and the primary feature, verify the prompt triggers at $0.3 \pm 0.1^\circ\text{C}$, and verify features stay within $\pm 10\%$ of the baseline value for changes below the threshold.
Conditioned eddy-current output shall remain within 0.1-3.2 V for all six required materials and no-sample.	Probe ADC_EDDY with an oscilloscope during all material tests and record min/max voltage.

Table 2. Eddy-current sensing subsystem requirements and verifications

2.5 Dielectric Sensing Subsystem

The dielectric subsystem distinguishes the two nonconductive required materials, cast acrylic (PMMA) and HDPE. Interdigitated copper electrodes produce a fringing electric field above the sensing surface. A nonconductive sample changes the effective capacitance and loss of this structure. An OPA2320-based analog front end [5] converts that small impedance change into a measurable amplitude/phase response for the STM32 ADC. The dielectric electrodes are covered by an insulating layer so the material never directly shorts the electrode structure. The analog front end is kept in the quiet analog region and powered from the separate 3.3 V analog rail. The excitation path is selected electronically from the same DDS used by the eddy-current channel, which reduces component count and makes the two electrical measurements time-coherent. This subsystem directly supports HLR 1 because it provides the only electrical feature that separates acrylic from HDPE, which produce no significant eddy-current response, and HLR 2 because its baseline subtraction and $\pm 10\%$ repeatability requirement keep repeated placements of the same polymer sample consistent.

Requirement	Verification
A 3 mm thick acrylic or HDPE sample shall produce at least 90% of the primary feature change produced by a 10 mm sample of the same material.	Place 3 mm and 10 mm coupons of each polymer 10 times each and compute the ratio of mean feature changes. Each ratio must be at least 0.9.
DC resistance between the sensing electrodes and a conductive sample placed on the platform shall exceed 1 Mohm.	Place a conductive plate on the sensing surface and measure resistance from the plate to each electrode using a DMM/megohmmeter.
Relative to the empty-platform baseline, the primary feature change shall be ≥ 10 times baseline standard deviation for both acrylic and HDPE.	Collect ≥ 20 empty readings and 10 readings for each polymer; calculate normalized feature change in units of baseline standard deviation.
At least one primary feature for acrylic vs. HDPE shall differ by ≥ 6 pooled standard deviations across ten trials each.	Collect 10 independent placements per polymer, compute pooled sigma and pairwise feature separation.
Ten removed/replaced measurements of the same polymer sample shall produce each primary feature within $\pm 10\%$ of the mean.	Perform ten trials, calculate mean and percent deviation, and confirm all trials meet the limit.
The same baseline procedure and $0.3\text{ }^{\circ}\text{C}$ re-baseline threshold shall apply to the dielectric channel.	Repeat the temperature sweep on ADC_DIEL and verify the dielectric feature stays within $\pm 10\%$ of baseline for changes below $0.3\text{ }^{\circ}\text{C}$.
Conditioned output shall remain within 0.1-3.2 V for both polymers and no-sample.	Probe ADC_DIEL with an oscilloscope during no-sample, acrylic, and HDPE conditions; verify no clipping.

Table 3. Dielectric sensing subsystem requirements and verifications

2.6 Mechanical Impulse and Damping Subsystem

This subsystem provides an independent feature when electrical measurements alone do not give sufficient separation. A 12 V push-pull solenoid, switched by an FQP30N06L MOSFET with an SS54 flyback path, applies a controlled impulse to the sample. A vibration sensor or microphone senses the ring-down, and an op-amp preamplifier and 5 kHz anti-alias filter condition the signal for ADC_VIB, sampled at 25 kHz. The primary feature is the damping time constant rather than resonant frequency, since resonance depends strongly on coupon geometry, and firmware estimates tau from the log-envelope slope of $A(t) = A_0 \exp(-t/\tau)$. Electrical sensing finishes before the solenoid fires, so switching noise cannot contaminate it and the ring-down capture fits inside the 5 s sequence of HLR 3. Where the dielectric margin between acrylic and HDPE is thin, the damping feature keeps HLR 1 achievable, and its $\pm 10\%$ repeatability limit extends that benefit to HLR 2.

Requirement	Verification
Solenoid driver shall deliver the same commanded pulse width on every trigger within $\pm 5\%$.	Trigger at least 20 pulses and measure MOSFET gate/drain pulse width on an oscilloscope. Compute maximum deviation from the programmed width.
During turn-off, peak switch-node voltage and current shall stay below 80% of the MOSFET and diode rated limits.	Use an oscilloscope with appropriate probes and a current measurement method to capture turn off transients for repeated actuations. Compare measured peaks to datasheet ratings.
The vibration chain shall use an anti-alias cutoff of 5 kHz and an ADC sample rate of at least 25 kHz, and shall record from impact until the envelope falls below 3 times the pre-impact RMS noise or 500 ms, whichever comes first.	Record the filter cutoff, ADC rate, and capture length for 10 impacts per material. Verify the sample rate is at least 5 times the cutoff, that capture ends at the $3\times$ noise criterion, and that the stored record contains the full decay.
Captured signals shall contain zero clipped samples and stay within 0.1-3.2 V across ten impacts on each required material.	Record raw ADC waveforms for 10 impacts/material and inspect min/max values and clipping count.
Ten impacts on the same removed/replaced sample shall produce damping features within $\pm 10\%$ of the mean, with ambient noise recorded each trial.	For a representative coupon, perform ten independent placements/impacts, calculate tau, mean, percent deviation, and pre-impact RMS noise.
Adding the damping feature shall improve classification accuracy relative to electrical features alone on the same test set.	Run the frozen test dataset through the classifier with and without the damping feature and compare percent correct using identical train/calibration splits.

Table 4. Mechanical impulse and damping subsystem requirements and verifications

2.7 Control and User-Interface Subsystem

The STM32G474RET6 is the central coordinator [2]. Its responsibilities are DDS configuration, multiplexer control, ADC acquisition, solenoid actuation, feature extraction, classification, OLED output, baseline management, nonvolatile calibration storage, and USB logging. SWD is exposed on J7 for programming/debugging and a BOOT0 jumper is included for recovery. The SSD1306 OLED is connected through I2C, and USB is protected by a USBLC6-2SC6 ESD device before reaching the MCU.

The intended firmware sequence is (1) ensure a valid baseline exists, (2) acquire 60 kHz and 240 kHz electrical responses, (3) determine whether the sample is conductive, (4) use the appropriate electrical feature set, (5) trigger the solenoid and capture the damping waveform, (6) normalize features against baseline/calibration data, (7) calculate class distances or scores, (8) apply an UNKNOWN threshold, (9) display the result/confidence, and (10) stream raw and computed features over USB for characterization. This sequence keeps the user interaction to a single measurement button while retaining detailed engineering data during development. This block owns the decision and the timing. It produces the displayed result that HLR 1 scores, enforces the 5 s limit in HLR 3 by sequencing every stage from a single button press, and supports HLR 2 by applying the same stored baseline and calibration data to every trial.

Metal versus nonmetal is decided first, by whether the eddy-current feature change exceeds 5 baseline standard deviations. Each calibrated class stores the mean and standard deviation of its feature vector. The firmware computes a standardized Euclidean distance d to each class, selects the smallest, and returns UNKNOWN if it exceeds a threshold set from calibration data. Confidence is $100 \times (1 - d/d_threshold)$, clipped to 0 to 100%. The planned timing budget is baseline check 0.1 s, electrical acquisition 1.0 s, solenoid pulse and ring-down capture 0.5 s, and classification and display under 0.1 s, about 2 s in total against the 5 s limit.

Requirement	Verification
Time from button press to displayed result shall be ≤ 5 s, with per-stage timing logged.	Use a logic analyzer/firmware timestamp log to record button events, stage completion times, and OLED updates over at least 20 trials.
All electrical acquisition shall finish before the solenoid pulse begins.	Expose a debug GPIO during electrical acquisition and observe it together with MOSFET gate on an oscilloscope/logic analyzer; verify no overlap.
OLED shall show one of the six calibrated materials or UNKNOWN plus an integer confidence from 0 to 100%.	Run known and deliberately out-of-set samples; record display output and verify formatting/range.
UNKNOWN threshold shall preserve $\geq 90\%$ in set identification while out-of-set stainless steel/zinc/titanium returns UNKNOWN in $>50\%$ of trials.	Tune threshold using calibration data, then evaluate a held-out in-set dataset and at least three out-of-set materials without changing the threshold.
Calibration reference data shall be stored in nonvolatile memory and retained across power cycles.	Write calibration, remove power for at least 30 s, reboot, and read back/calibrate without PC intervention; compare stored values.

Raw and computed features for each trial shall be transferred to a PC over USB in a machine readable format.	Connect to the USB virtual serial interface and capture at least 20 trials. Parse the output automatically and verify all required fields are present.
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Table 5. Control and user-interface subsystem requirements and verifications

2.8 Power Subsystem

A 12 V external adapter is the system input. The solenoid branch remains on 12 V, while an R-78E5.0-0.5 regulator generates an intermediate 5 V rail. The 5 V rail supplies the INA828 and feeds two TLV73333 regulators that create separate 3.3 V digital and 3.3 V analog rails. Input protection includes a resettable fuse and reverse-polarity Schottky diode. Local bulk and ceramic decoupling capacitors are distributed across the PCB. The separate analog rail and physical separation of the solenoid switching loop are intended to reduce measurement corruption from digital/switching noise. The PCB exposes dedicated test points for 12 V, 5 V, 3.3 V digital, 3.3 V analog, and GND so first power-up can be performed from a current-limited bench supply. The solenoid MOSFET and flyback path are placed in the power/solenoid region to keep the high-current loop compact. This subsystem adds no measurement capability of its own. It protects HLRs 1 and 2 by keeping supply noise from shifting any primary feature by more than 2%, and protects HLR 3 by preventing MCU resets that would interrupt the 5 s sequence.

Requirement	Verification
Peak input current during worst-case operation shall stay below 80% of the resettable fuse hold current and the reverse-polarity diode current rating.	Measure input current with a current probe over 1000 solenoid actuations with all sensing active, verify the fuse never trips, and compare the peak to both ratings.
12 V rail shall remain ≥ 11.4 V during solenoid pulses.	Probe 12 V rail at the solenoid connector while repeatedly pulsing the solenoid; record minimum voltage.
The 5 V rail at the INA828 supply pin shall remain within $5\text{ V} \pm 5\%$ with no more than 50 mVpp ripple during solenoid firing.	Probe the INA828 supply pin with a 20 MHz bandwidth-limited oscilloscope during repeated solenoid pulses and record the minimum, maximum, and peak-to-peak ripple.
3.3 V digital rail shall remain between 3.135 V and 3.465 V with zero MCU resets over 1000 solenoid actuations.	Monitor 3.3 V digital rail and MCU reset/debug status while automatically actuating the solenoid 1000 times.
3.3 V analog rail noise shall not shift any primary feature by more than 2% relative to a battery-powered reference.	Measure the same reference sample using normal regulated power and a low-noise battery/reference supply; compare extracted features.

A solenoid actuation immediately before an electrical measurement shall change the measured feature by $\leq 2\%$ compared with no prior actuation.	Alternate trials with and without a pre measurement solenoid pulse using the same sample and calculate percent feature difference.
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Table 6. Power subsystem requirements and verifications

2.9 Tolerance Analysis

The most critical feasibility risk is whether the eddy-current channel can reliably separate the four conductive materials, especially 6061 aluminum and C360 brass, without thermal drift consuming the feature separation margin. The approved proposal therefore analyzes skin depth, surface resistance, expected phase separation, and coil-temperature drift.

2.9.1 Skin Depth versus Sample Thickness

The skin depth of a conductor at excitation frequency f is:

$$\delta = 1 / \sqrt{(\pi f \mu_0 \mu_r \sigma)}$$

where σ is conductivity, μ_r is relative permeability, and $\mu_0 = 4 \pi \times 10^{-7}$ H/m. Using the preliminary material properties from the proposal [8] gives:

Material	σ (S/m)	μ_r	δ @ 60 kHz	δ @ 240 kHz	3 mm/ δ @ 60 kHz
C110 copper	5.8×10^7	1	0.27 mm	0.14 mm	11.1
6061 aluminum	2.5×10^7	1	0.41 mm	0.21 mm	7.3
C360 brass	1.5×10^7	1	0.53 mm	0.27 mm	5.7
1018 mild steel	6×10^6	100 (assumed)	0.08 mm	0.04 mm	35.8

Table 7. Skin depth of the conductive materials at 60 kHz and 240 kHz

Field amplitude falls approximately as $\exp(-t/\delta)$. The worst case is brass at 60 kHz, where 3 mm corresponds to about 5.7 skin depths and the remaining field is approximately $\exp(-5.7) = 0.3\%$. Thus the 3 mm minimum sample thickness is sufficient for the preliminary eddy-current model.

2.9.2 Surface Resistance and Conductive-Material Separation

The high-frequency surface resistance is approximated by:

$$R_s = 1 / (\sigma \delta)$$

Material	R_s @ 60 kHz	R_s @ 240 kHz
C110 copper	63.9 micro-ohm/sq	127.8 micro-ohm/sq

6061 aluminum	97.3 micro-ohm/sq	194.7 micro-ohm/sq
C360 brass	125.7 micro-ohm/sq	251.3 micro-ohm/sq

Table 8. Estimated surface resistance of C110 copper, 6061 aluminum, and C360 brass

The closest pair is 6061 aluminum and C360 brass, which differ by roughly 29% in this surface resistance estimate. Using the proposal's illustrative coil model with coupling factor K about 400, $L = 10$ microhenry, and coil self-resistance $R_0 = 1$ ohm, the coil impedance magnitude is: $|Z| = \sqrt{R_0^2 + (2\pi f L)^2}$

At 60 kHz, $|Z|$ is approximately 3.90 ohm. The illustrative reflected-resistance/phase values are 25.6 mOhm / 0.376 deg for copper, 38.9 mOhm / 0.572 deg for aluminum, and 50.3 mOhm / 0.738 deg for brass. Therefore aluminum and brass differ by about 11.3 mOhm or 0.166 deg. Treating the +/-10% repeatability requirement as a 3-sigma bound gives sigma approximately 3.3% of each material's mean, or approximately 0.019 deg for aluminum and 0.024 deg for brass under the illustrative model. The pooled standard deviation of the two is approximately 0.0218 deg, so the aluminum-brass phase separation is approximately $0.166/0.0218 = 7.6$ pooled standard deviations, which exceeds the 6-sigma subsystem target. Treating the 0.3 °C re-baseline threshold as a worst-case self-resistance error of 1.18 mΩ, about 0.8 pooled standard deviations, the margin falls to about 6.8 pooled standard deviations, which still meets the 6-sigma target. The model parameters K , L , and R_0 will be replaced with measured values from the fabricated coil during characterization. The analysis is used here to show that the expected scale of separation is measurable.

2.9.3 Coil Temperature Drift

Copper magnet wire has a resistance temperature coefficient of about 0.393%/degC. The corresponding self-resistance drift is:

$$\Delta R_{\text{drift}} = \alpha R_0 \Delta T$$

Using $R_0 = 1$ ohm, a change of only about 0.33 degC produces a 1.30 mOhm change, comparable to the illustrative one-sigma aluminum resistance budget. Thermal drift can therefore consume the classification margin if an empty-platform reference is not updated. This directly motivates the power up baseline and temperature-triggered re-baseline requirement. The re-baseline threshold is set at 0.3 °C.

2.9.4 Secondary Risk: Acrylic versus HDPE

The dielectric channel has a separate tight-margin risk. Using the proposal's simple cover/sample effective-permittivity approximation [9], ϵ_{eff} is approximately 3.55 for acrylic and 3.35 for HDPE, only about a 6% difference. This is substantially smaller than the conductive-material separation and is why the dielectric channel requires baseline subtraction, careful analog layout, repeated characterization, and the independent mechanical damping feature.

3. Cost and Schedule

3.1 Cost Analysis

3.1.1 Labor

The labor model follows the ECE 445 rubric: hourly engineering salary x 2.5 overhead multiplier x estimated project hours. UIUC reports 2024-2025 average starting salaries of \$87,429 for Electrical Engineering and \$119,064 for Computer Engineering [11]. Because the team is an ECE team and individual major information is not needed for the estimate, we use the midpoint, \$103,246.50/year. Assuming 2,080 work hours/year gives an estimated engineering rate of \$49.64/hour. Estimated labor per member = \$49.64/hour x 2.5 x 120 hours = \$14,892.00.

Team member	Assumed rate	Hours	2.5x loaded labor cost
Shritan Bhupathiraju	\$49.64/hr	120	\$14,892.00
Sachith Chandran	\$49.64/hr	120	\$14,892.00
Siddharth Gupta	\$49.64/hr	120	\$14,892.00
Total	\$49.64/hr	360	\$44,676.00

Table 9. Estimated labor cost per team member

3.1.2 Parts and Services

The following is a budgetary single-prototype estimate based on the selected design. ECE E-Shop stock may reduce out-of-pocket cost, and exact vendor pricing will be updated as components are ordered. The PCB fabrication line reflects the nominal course PCBWay prototype quote; the course may cover this expense.

Description	Manufacturer / Part	Qty.	Est. unit	Est. total
MCU	STMicroelectronics STM32G474R ET 6	1	\$12.00	\$12.00
DDS waveform generator	Analog Devices AD9833BRMZ	1	\$9.00	\$9.00
8:1 precision analog mux	Texas Instruments TMUX1108PWR	1	\$2.50	\$2.50
Instrumentation amplifier	Texas Instruments INA828ID	1	\$7.00	\$7.00

Dual precision op amp	Texas Instruments OPA2320AID	2	\$4.50	\$9.00
Precision op amp	Texas Instruments OPA320AIDBVR	1	\$2.00	\$2.00
3.3 V LDO	Texas Instruments TLV73333PDBVR	2	\$1.50	\$3.00
5 V regulator	RECOM R-78E5.0-0.5	1	\$9.00	\$9.00
USB ESD protection	ST USBLC6-2SC6	1	\$1.00	\$1.00
Solenoid MOSFET	onsemi/Fairchild FQP30N06L	1	\$1.20	\$1.20
Schottky protection diodes	SS54	2	\$0.50	\$1.00
25 MHz oscillator	3.3 V, 3.2 x 2.5 mm	1	\$2.50	\$2.50
8 MHz crystal	SMD crystal	1	\$1.00	\$1.00
USB-C receptacle	USB 2.0 Type-C	1	\$1.50	\$1.50
OLED	SSD1306 I2C module	1	\$5.00	\$5.00
Mechanical actuator	12 V push-pull solenoid	1	\$12.00	\$12.00
Vibration sensor	Piezo or MEMS sensor	1	\$3.00	\$3.00
Eddy-current sensor	Ferrite-backed coil materials	1	\$8.00	\$8.00
Passives/connectors/test points	0805/SMD + headers	1 lot	\$12.00	\$12.00

2-layer PCB fabrication	PCBWay, <=100 mm x 100 mm, 10 pcs	1 lot	\$5.00	\$5.00
Enclosure/top plate/fasteners	Mechanical materials	1 lot	\$10.00	\$10.00
Certified material coupons	6061, C110, C360, 1018, PMMA, HDPE	1 lot	\$20.00	\$20.00
Parts subtotal				\$136.70

Table 10. Bill of materials for a single prototype

Grand Total: Labor + Parts: \$44,812.70

3.2 Schedule

The schedule below starts with the current week of September 28. It is an internal engineering schedule; official course deadlines remain governed by the ECE 445 calendar. PCB review, Gerber audit, and board ordering are front-loaded so the 7-10 day fabrication/arrival lead time described in the course PCB review material does not delay assembly [12]

Week	Team milestone	Shritan	Sachith	Siddharth
9/28	TA PCB review; finalize design document; finish Gerbers/PCBWay audit and order	Review eddy current path and coil connector; verify analog front-end parts	Review dielectric/vibration paths; confirm solenoid/sensor parts	PCB/DRC/ Gerbers; design document integration; MCU/USB/SWD review
10/5	Procure remaining parts; bench prototypes while PCB is fabricated	Build/measure coil; characterize 60/240 kHz response on known metals	Prototype dielectric electrodes and vibration sensor/solenoid fixture	Develop STM32 drivers for DDS, ADC, OLED, USB logging
10/12	PCB assembly and staged board bring-up	Assist analog assembly; verify excitation/eddy channel	Assist analog/mechanical assembly; verify dielectric/vibration channel	Power rails, SWD, MCU clock, USB, basic firmware bring-up
10/19	Electrical sensing integration	Collect conductor response data; tune coil/front	Collect acrylic/HDPE dielectric data	Implement synchronous detection and

		end		baseline manager
10/26	Mechanical subsystem integration	Support feature analysis and enclosure sensor placement	Tune solenoid pulse, vibration gain/filter, damping extraction	Integrate GPIO timing, ADC capture, logging
11/2	Full sensing sequence and PC data logging	Characterize metal repeatability and thermal drift	Characterize polymer/mechanical repeatability	End-to-end firmware sequence and structured USB output
11/9	Calibration and classifier	Prepare conductive material calibration dataset	Prepare dielectric/damping calibration dataset	Implement classifier, confidence, UNKNOWN threshold, flash storage
11/16	Formal R&V testing	Run eddy-current R&V tests and analyze pairwise sigma separation	Run dielectric/mechanical R&V tests	Run timing/UI/power/USB R&V tests; consolidate results
11/23	Accuracy/repeatability refinement	Investigate metal misclassifications and baseline drift	Investigate polymer/mechanical misclassifications	Tune thresholds/classifier and finalize integrated test firmware
11/30	Mock demo, documentation, contingency rework	Demo preparation; repeat critical sensor tests	Demo preparation; mechanical/enclosure cleanup	Demo integration, logs, final firmware/documentation
12/7	Final demonstration contingency	Final eddy-current checks	Final dielectric & vibration checks	Firmware freeze and demo run

Table 11. Weekly project schedule and task assignments

4. Discussion of Societal Impact, Engineering Standards, Ethics, and Safety Considerations

4.1 Societal Impact

MaterialID is intended as a preliminary identification aid for machine shops, makerspaces, and

teaching laboratories. A successful low-cost instrument can reduce the amount of usable stock discarded merely because labels are missing and can reduce incorrect machining or handling of unknown stock. The primary positive impact is therefore economic and environmental: reuse of material already on hand reduces replacement purchases and unnecessary waste. The project is not intended to compete with certified elemental-analysis equipment when composition certification is required.

The device does not use accounts, cameras, cloud services, or personal data. If a microphone is selected for the mechanical measurement, only a short transient after the controlled solenoid impact is needed and permanent audio recording is unnecessary. This keeps privacy concerns minimal.

There is also a modest public health and safety benefit, since a quick first-pass identification gives operators data in place of a guess when choosing machining or joining parameters, and UNKNOWN results direct users to a certified method. MaterialID is not a substitute for certified identification. Socially and culturally, the one-button interface gives students and makerspace members access to identification skills that otherwise depend on experienced machinists, and it supports reuse of leftover stock. Globally, the device uses commodity parts, runs from a standard 12 V adapter, and needs no network or accounts, so it suits schools and workshops with limited infrastructure.

4.2 Engineering Standards

The project will use the following standards and design practices, consistent with the approved proposal:

- IEC 62368-1 [6] as a relevant equipment-safety reference for low-voltage electronic equipment.
- FCC 47 CFR Part 15, Subpart B as a reference for unintentional radiated emissions from digital/excitation circuitry operating above 9 kHz.
- IPC-2221 for general PCB design practices and IPC-A-610 as an assembly/workmanship reference.
- RoHS restricted-substance limits as a component/solder selection practice, although this student prototype is not being sold commercially.
- USB 2.0 electrical routing guidance for the development interface, including approximately 90 ohm differential impedance and a continuous return path.
- ECE 445 PCB fabrication constraints and safety procedures, including a ≤ 100 mm x 100 mm board, manufacturer-compatible DRC, safe soldering, and current-limited powered bring-up.

4.3 Ethics

The IEEE Code of Ethics requires engineers to prioritize public safety and to make honest and realistic claims about system capability [1]. The central ethical concern is that a user could treat a MaterialID result as certified composition analysis. A misclassification could be dangerous if the material is then used in a safety-critical structure or if an out-of-set hazardous material is treated as a benign calibrated class. The firmware therefore includes an UNKNOWN outcome rather than forcing the closest class, and the OLED presents a confidence value. Documentation and demonstrations will explicitly state that the calibrated set is limited to six specified grades/materials.

The device must not be used as the sole verification method for aerospace structures, medical equipment, pressure vessels, load-bearing structures, or hazardous/regulated material screening. Examples of misuse include magnesium being mistaken for aluminum before machining or beryllium copper being mistaken for ordinary copper. The project team will report accuracy, uncertainty, and failed cases rather than selectively presenting only successful trials. The project follows IEEE Code of Ethics items I.1 (holding paramount the safety, health, and welfare of the public) and I.5 (being honest and realistic in stating claims based on

available data) [1]. The ACM Code of Ethics applies through Principle 1.2 (avoid harm) and Principle 2.5 (give thorough evaluations of a system and its risks) [13], since a user could over-trust the confidence value shown on the display. In line with the course ethics guidelines [14], the team will record all test data, report failed trials, and credit all outside sources. No new ethical concerns have arisen since the proposal.

4.4 Electrical and Mechanical Safety

The external adapter is low voltage, so electric shock risk is limited [7]. The main electrical hazards are short circuits during bring-up, regulator or trace overheating, and the inductive turn-off transient from the solenoid. Initial power-up will use a current-limited bench supply. Power rails will be checked for shorts before energizing, and 12 V/5 V/3.3 V test points provide accessible measurement locations. The solenoid driver uses a flyback diode and a MOSFET selected with voltage/current margin; turn-off transients will be verified by oscilloscope before extended operation.

The solenoid is also a moving mechanical component and can create a pinch/impact hazard. It will be mounted below the sensing platform and enclosed so fingers cannot enter the plunger path during normal use. The actuator will only be energized for short pulses, and repeated-operation testing will monitor heating. Externally accessible surfaces will be checked for unsafe temperature rise during extended test sequences.

4.5 Risk-Mitigation Procedures

1. Before first power, verify resistance/continuity between each supply rail and GND and confirm no unexpected low-resistance short.
2. Use a current-limited bench supply for initial 12 V bring-up; validate 5 V, 3.3 V digital, and 3.3 V analog rails before installing/activating all loads.
3. Program and debug through SWD before enabling the solenoid branch. Keep electrical sensing disabled during first actuator tests.
4. Capture MOSFET drain voltage and solenoid current during turn-off and verify peak stress remains below 80% of component ratings.
5. Keep the solenoid mechanism covered during operation and do not hold a sample by hand over a moving actuator during automated sequences.
6. Use only known/certified calibration coupons for training/reference data. Keep calibration and held-out test coupons separated and documented.
7. Log all raw features during verification so anomalous classifications can be traced to sensor or calibration behavior.
8. If the system is uncertain or a sample falls outside the calibrated distribution, return UNKNOWN and instruct the user to use an appropriate certified identification method.

5. References

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