

MaterialID: Multi-Modal Material Identification System

Shritan Bhupathiraju (shritan2)
Sachith Chandran (src14)
Siddharth Gupta (sg96)

ECE 445: Team 47

TA: Aniket Chatterjee

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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 as many common engineering materials have similar appearances.

Incorrect material identification can lead to several problems. Different materials may require different machining parameters, joining processes, or handling procedures. Metals that appear visually similar can have very different conductivity, magnetic behavior, strength, corrosion resistance, and machinability. Plastics can also appear nearly identical while exhibiting significantly different mechanical and thermal properties.

As a result, unidentified stock may be incorrectly processed or discarded entirely. Existing low-cost tools are generally limited to only one type of measurement. A magnet can separate many ferromagnetic materials from non-ferromagnetic materials, but it provides little information about aluminum, copper, brass, or plastics. Electrical conductivity measurements can distinguish conductive materials but cannot identify nonconductors. Visual inspection is highly dependent on surface finish as well as user experience.

Although there are more sophisticated instruments such as X-ray fluorescence analyzers which can identify elemental composition, these devices are expensive and unnecessary for basic identification in teaching laboratories and small machine shops.

A lower-cost material identification system that combines several physical measurements could provide a practical method for distinguishing a constrained set of common engineering materials while reducing material waste and incorrect material usage.

1.2 Solution

MaterialID will be an instrument capable of identifying an unknown material by combining several independent physical measurements.

The user will place a sample on a sensing platform and press a measurement button. The device will first determine whether the material is electrically conductive using an eddy-current sensor. For conductive materials, the system will measure the sample's electromagnetic response at multiple excitation frequencies. The magnitude and phase of this response will provide features related to electrical conductivity and magnetic permeability.

If the material is nonconductive, the system will use a PCB-based fringing-field capacitive sensor to characterize its dielectric response. This provides a measurable feature that can help distinguish insulating materials such as acrylic and HDPE.

A third sensing method will measure mechanical damping. A solenoid will apply a controlled impulse to the sample, and a microphone or vibration sensor will capture the resulting ring-down response. The decay of this response provides another feature that can help distinguish materials whose electrical properties alone are insufficient.

An STM32 microcontroller will coordinate the sensors, acquire the measurements, extract the relevant features, and compare them against a calibrated reference table. The system will then display the predicted material and a confidence value on an OLED display.

The required material set will consist of the following specific alloys and grades, which will be sourced from certified stock so that composition is known:

- 6061-T6 aluminum
- C110 copper
- C360 brass
- 1018 mild steel
- cast acrylic (PMMA)
- HDPE

Alloy is specified rather than base metal because electrical conductivity varies substantially within a metal family. 2024 and 7075 aluminum have conductivities near those of common brasses, so a general "aluminum vs. brass" claim would not be supportable with eddy-current sensing alone.

1.3 Visual Aid

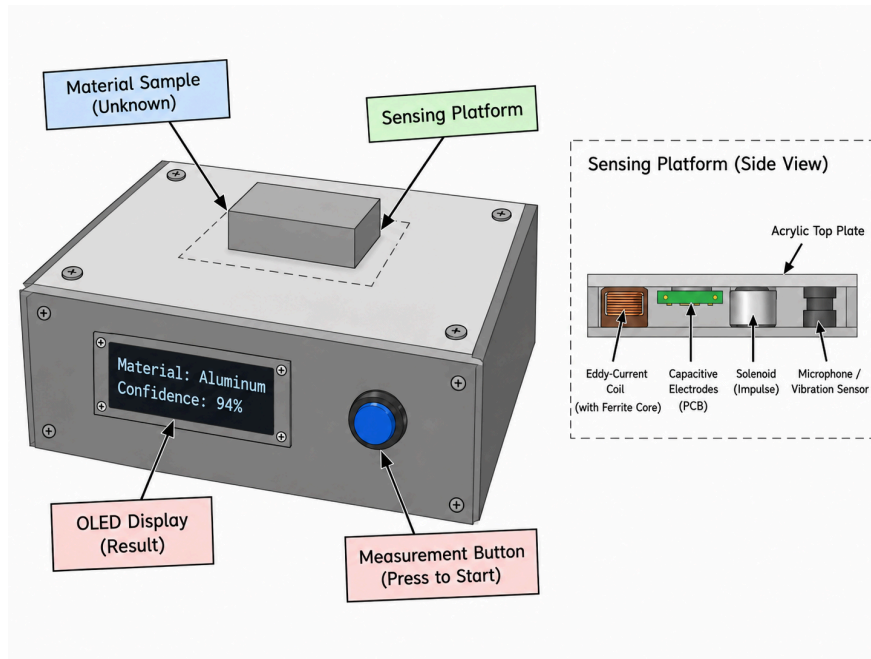


Figure 1: Intended use of MaterialID.

1.4 High-Level Requirements

1. 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. A controlled trial consists of placing a single sample on the platform, pressing the measurement button, and recording the displayed result, using only samples excluded from calibration.
2. Ten repeated identifications of the same physical sample, with the sample removed from the platform and re-placed between trials, shall return the same displayed material in at least **9 of the 10 trials**.
3. 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.

2. Design

2.1 Block Diagram

Figure 2: MaterialID system block diagram.

The system will be divided into six main subsystems:

- excitation and signal-processing subsystem
- eddy-current sensing subsystem
- dielectric sensing subsystem
- mechanical impulse and damping subsystem
- control and user-interface subsystem
- power subsystem

Figure 2 shows the major connections between these subsystems.

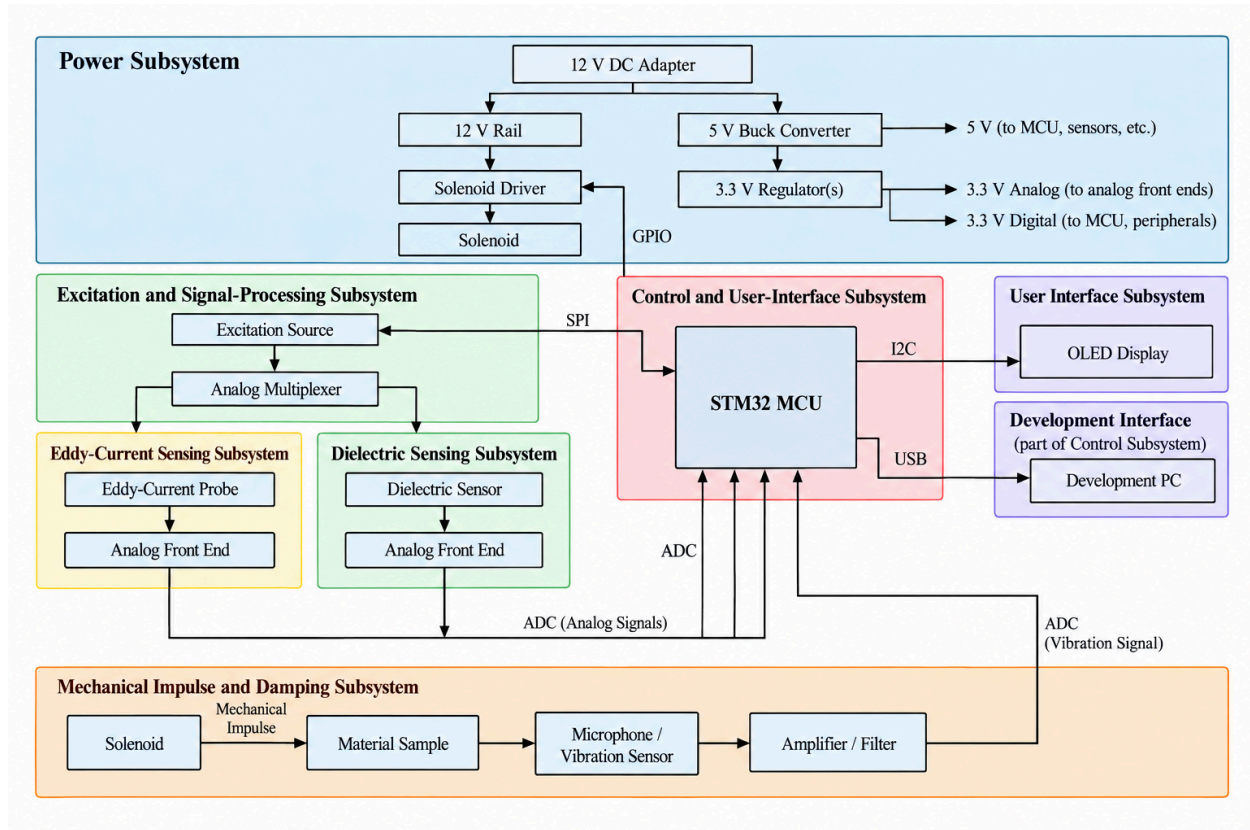


Figure 2: MaterialID system block diagram.

Figure 2 labels each supply rail (12 V, 5 V, 3.3 V digital, and 3.3 V analog) and each data interface (SPI to the waveform generator, I2C to the OLED, GPIO to the solenoid driver, ADC inputs to the MCU, and USB to the development PC). The OLED and the USB development interface are drawn as separate blocks for clarity but belong to the control and user-interface subsystem described in Section 2.2.5.

2.2 Subsystem Overview

2.2.1 Excitation and Signal-Processing Subsystem

The excitation and signal-processing subsystem generates the electrical signals used by the eddy-current and dielectric sensors.

A programmable waveform source will generate sinusoidal excitation signals at multiple frequencies[3]. A buffer stage will drive the selected sensor, and an analog multiplexer will choose between the eddy-current and dielectric sensing paths.

The multiplexer is placed on the excitation side rather than at the sensing electrodes. The TMUX1108's off-state capacitance is 60 pF at the common node, which is large relative to the capacitive sensor's signal, so placing it there would load the dielectric front end and reduce sensitivity [10].

The STM32 will simultaneously sample a reference excitation signal and the sensor response[2]. Firmware will use synchronous detection to calculate magnitude and phase features from the measured waveforms.

This subsystem provides the controlled excitation and signal-processing functions needed by both electrical sensing methods.

Tentative components include:

- STM32G474RET6
- AD9833 programmable waveform generator
- TMUX1108 analog multiplexer
- output power buffer capable of driving the eddy-current coil

2.2.2 Eddy-Current Sensing Subsystem

The eddy-current subsystem will characterize conductive samples without requiring direct electrical contact.

A ferrite-backed coil located beneath the sensing surface will create an alternating magnetic field. When a conductive sample is placed above the coil, eddy currents induced in the material modify the effective impedance of the sensing coil.

Different materials produce different changes in magnitude and phase depending on electrical conductivity and magnetic permeability[8], [9]. Measuring the response at more than one excitation frequency provides additional information for distinguishing the required conductive material classes.

The subsystem will primarily distinguish:

- aluminum

- copper
- brass
- mild steel

The INA828 requires a minimum single-supply voltage of 4.5 V, so it will be powered from the 5 V rail rather than the 3.3 V rail used elsewhere in the system [4]. Its output is scaled and level-shifted to fit within the STM32 ADC's 0.1-3.2 V input range before digitization, consistent with the ADC input constraint in requirement 2.3.1, R6.

2.2.3 Dielectric Sensing Subsystem

The dielectric sensing subsystem will characterize materials that do not produce a significant eddy-current response.

An interdigitated electrode structure implemented on the PCB will generate a fringing electric field above the sensing platform. Placing a nonconductive material over the electrode changes the effective capacitance and dielectric loss of the sensor.

An analog front end will condition the resulting signal for the STM32 ADC. The measured magnitude and phase features will be compared with calibrated reference measurements.

The primary purpose of this subsystem will be to distinguish:

- acrylic
- HDPE

Tentative components include:

- PCB interdigitated sensing electrode
- OPA2320 operational amplifier [5]
- passive feedback and filtering components

2.2.4 Mechanical Impulse and Damping Subsystem

The mechanical subsystem will provide an additional material feature based on vibration damping.

A push-pull solenoid beneath the platform will apply a repeatable mechanical impulse to the sample. The solenoid will be controlled using a logic-level MOSFET and protected by a flyback diode.

A microphone or vibration sensor will capture the transient response of the material after the impulse. Firmware will analyze the decay envelope and other time- or frequency-domain characteristics.

Mechanical damping is used instead of only resonant frequency because resonance frequency depends heavily on sample geometry. Damping provides an additional feature that can help differentiate material groups.

Tentative components include:

- 12 V push-pull solenoid
- logic-level MOSFET
- flyback diode
- INA180 current-sense amplifier[6]
- MEMS microphone or piezoelectric sensor
- op-amp preamplifier and anti-alias filter

2.2.5 Control and User Interface Subsystem

The STM32 microcontroller will coordinate the complete measurement sequence.

The MCU will:

- configure the excitation source
- select sensing paths
- acquire ADC measurements
- control the solenoid
- calculate electrical and mechanical features
- perform material classification
- control the OLED display
- provide USB communication for calibration and debugging

The material classifier will compare the measured features against calibrated reference values. If the measurements do not fall sufficiently close to one of the known material classes, the device will return "UNKNOWN" rather than forcing a classification.

An SSD1306 OLED will display the predicted material and confidence value.

2.2.6 Power Subsystem

A 12 V external adapter will power the system. The solenoid will operate directly from the 12 V rail. A buck converter steps this down to an intermediate 5 V rail, which powers the INA828 and other components that need more headroom than 3.3 V provides. Separate 3.3 V digital and

analog rails are regulated from the 5 V rail, with the analog rail isolated by filtering to keep switching noise and solenoid transients from coupling into the measurement path.

2.3 Subsystem Requirements

Throughout this section, HLR 1, HLR 2, and HLR 3 refer to the three high-level requirements in Section 1.4. A *primary feature* is a baseline-subtracted magnitude or phase measured at one excitation frequency (eddy-current and dielectric subsystems) or the damping decay time constant (mechanical subsystem). *Pooled standard deviation* for two classes is the square root of the average of their two variances, computed over ten trials each.

2.3.1 Excitation and Signal-Processing Subsystem

Contribution to the design: This subsystem produces the excitation and the magnitude and phase measurements on which every electrical feature depends. It supports HLR 1 (classification accuracy) and HLR 2 (repeatability), and its acquisition time counts toward HLR 3.

Interfaces: It is configured by the MCU over SPI and drives the selected sensor. It returns the excitation reference and sensor response to the MCU ADC inputs.

1. The subsystem shall generate sinusoidal excitation at 60 kHz $\pm 1\%$ and 240 kHz $\pm 1\%$, selectable by firmware.
2. The drive amplitude shall match between the two frequencies within $\pm 5\%$ and remain stable within $\pm 2\%$ over any 5 s measurement.
3. The MCU shall sample the reference and sensor-response channels simultaneously, with inter-channel skew of at most 1° at 240 kHz and at least 8 samples per excitation period.
4. Synchronous detection shall recover magnitude within $\pm 1\%$ and phase within $\pm 1^\circ$ of a known RC reference network at both frequencies.
5. Sensor-path selection shall be performed by firmware only, shall settle within 10 ms, and shall attenuate the unselected path by at least 40 dB.
6. The reference and response signals at the ADC pins shall remain within 0.1–3.2 V for every required material and for the no-sample condition.

2.3.2 Eddy-Current Sensing Subsystem

Contribution to the design: This subsystem distinguishes the four conductive materials without electrical contact, which covers most of the required set. It supports HLR 1 and HLR 2, and its output also tells the classifier whether a sample is conductive.

Interfaces: It is driven by the excitation from 2.3.1 and outputs a conditioned signal to the MCU ADC.

1. The subsystem shall accept flat samples at least 3 mm thick that fully cover the sensor's active area.
2. Relative to the empty-platform baseline, the primary feature change shall be at least $10\times$ the baseline standard deviation for each conductive material and no more than $3\times$ for acrylic and HDPE.
3. For each of the six pairs among aluminum, copper, brass, and mild steel, at least one primary feature shall differ by at least 6 pooled standard deviations across ten trials.
4. Ten consecutive measurements of the same sample, removed and re-placed between trials, shall produce each primary feature within $\pm 10\%$ of the mean.
5. The system shall acquire an empty-platform baseline at power-up and on user request. It shall prompt for a new baseline when board temperature has changed by more than a threshold, set during characterization, that keeps baseline drift within the $\pm 10\%$ repeatability limit.
6. The conditioned output shall remain within 0.1–3.2 V for all six materials and the no-sample condition.

2.3.3 Dielectric Sensing Subsystem

Contribution to the design: This subsystem separates acrylic from HDPE, which the eddy-current path cannot do. It supports HLR 1 and HLR 2.

Interfaces: It is driven by the excitation from 2.3.1 and outputs a conditioned signal to the MCU ADC.

1. The subsystem shall accept flat, nonconductive samples that fully cover the sensor's active area.
2. The electrodes shall be covered by an insulating layer such that the DC resistance between the electrodes and a conductive sample exceeds 1 M Ω .
3. Relative to the empty-platform baseline, the primary feature change shall be at least $10\times$ the baseline standard deviation for both acrylic and HDPE.
4. For acrylic and HDPE, at least one primary feature shall differ by at least 6 pooled standard deviations across ten trials each.
5. Ten consecutive measurements of the same sample, removed and re-placed between trials, shall produce each primary feature within $\pm 10\%$ of the mean.
6. The baseline acquisition and re-baseline prompt described in 2.3.2, requirement 5 shall also apply to this subsystem.
7. The conditioned output shall remain within 0.1–3.2 V for both materials and the no-sample condition.

2.3.4 Mechanical Impulse and Damping Subsystem

Contribution to the design: This subsystem supplies an independent damping feature for material pairs that the electrical features may not separate reliably. It supports HLR 1 and HLR 2, and its duration counts toward HLR 3.

Interfaces: It is triggered by an MCU GPIO and powered from the 12 V rail. It outputs a vibration or audio signal to the MCU ADC.

1. The driver shall deliver the same solenoid pulse width on every trigger, within $\pm 5\%$.
2. During turn-off, peak switch-node voltage and current shall not exceed 80% of the switching device's rated limits, verified by oscilloscope.
3. The sensor signal shall be captured from impact until the response decays to the noise floor, at a sampling rate of more than twice the anti-alias filter cutoff.
4. The captured signal shall contain zero clipped samples and stay within 0.1–3.2 V across ten impacts on each of the six materials.
5. Ten consecutive impacts on the same sample, removed and re-placed between trials, shall produce the damping feature within $\pm 10\%$ of the mean, with the ambient noise level recorded during each test.
6. Adding the damping feature to the classifier shall raise classification accuracy over electrical features alone on the same test set.

2.3.5 Control and User Interface Subsystem

Contribution to the design: This subsystem sequences the measurements, classifies the sample, and displays the result. It directly implements HLR 3 and reports the outcome for HLR 1.

Interfaces: It drives the excitation source over SPI, the OLED over I2C, and the solenoid driver over GPIO. It exchanges calibration and debug data with a PC over USB.

1. The time from button press to result on the OLED shall be at most 5 s, and firmware shall log per-stage timing so each stage's contribution can be verified.
2. All electrical acquisition shall complete before the solenoid pulse begins.
3. The system shall require only the button press, with no entry of material type or sample dimensions.
4. The OLED shall show either one of the six calibrated materials or "UNKNOWN", plus an integer confidence value from 0 to 100%.
5. The "UNKNOWN" threshold shall be set from calibration data such that all six calibrated materials are still identified correctly in at least 90% of trials. Out-of-set materials (e.g., stainless steel, zinc, titanium) shall return "UNKNOWN" in more than half of trials.
6. Calibration reference data shall be stored in nonvolatile memory and retained across power cycles.
7. The system shall transfer raw and computed features for each trial to a PC over USB in a machine-readable format.

2.3.6 Power Subsystem

Contribution to the design: This subsystem keeps rail noise and solenoid transients from corrupting measurements or resetting the MCU, which underpins the repeatability in HLR 2.

Interfaces: It takes 12 V DC $\pm 5\%$ from an external adapter. It supplies a 12 V rail to the solenoid, an intermediate 5 V rail, and 3.3 V digital and analog rails.

1. The adapter shall be rated for at least $1.25\times$ the measured peak system load.
2. The 12 V rail shall stay at or above 11.4 V during solenoid pulses.
3. The 5 V rail shall remain within 5 V $\pm 5\%$ under all load conditions.
4. The 3.3 V digital rail shall remain within 3.135–3.465 V at all times, with zero MCU resets over 1000 consecutive solenoid actuations.
5. The 3.3 V analog rail noise shall not shift any measured primary feature by more than 2% relative to a battery-powered reference.
6. Actuating the solenoid immediately before an electrical measurement shall change the measured feature by no more than 2% compared with no actuation.

2.4 Tolerance Analysis

Risk identified: The eddy-current subsystem must distinguish four conductive materials, and the two electrically closest (aluminum and brass) are the pair most likely to violate HLR 2 if coil drift or measurement noise eats into their separation. This section shows (1) that 3 mm samples are thick enough for all four metals, and (2) that the aluminum–brass pair is separable with margin, provided the system re-baselines against temperature drift as specified in 2.3.2.

2.4.1 Skin depth vs. 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.

The relative permeability of mild steel is assumed to be 100 for the preliminary skin-depth calculation.

Material	σ (S/m)	μ_r	δ at 60 kHz	δ at 240 kHz	3 mm / δ (60 kHz)
Copper	5.8×10^7	1	0.27 mm	0.14 mm	11.1

Aluminum (6061)	2.5×10^7	1	0.41 mm	0.21 mm	7.3
Brass	1.5×10^7	1	0.53 mm	0.27 mm	5.7
Mild steel	6×10^6	100	0.08 mm	0.04 mm	35.8

[8], [9]

Field amplitude falls off as $e^{-(t/\delta)}$, so at 3 mm the worst case (brass, 60 kHz, 5.7 skin depths) attenuates the field to $e^{(-5.7)} \approx 0.3\%$, and 3 mm is effectively opaque to eddy currents for every material in the set. This confirms the 3 mm minimum in requirement 2.3.2, R1.

2.4.2 Surface resistance and separability

The high-frequency surface resistance is:

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

Material	R_s at 60 kHz	R_s at 240 kHz
Copper	63.9 $\mu\Omega/\text{sq}$	127.8 $\mu\Omega/\text{sq}$
Aluminum (6061)	97.3 $\mu\Omega/\text{sq}$	194.7 $\mu\Omega/\text{sq}$
Brass	125.7 $\mu\Omega/\text{sq}$	251.3 $\mu\Omega/\text{sq}$

[8]

The closest pair is aluminum and brass, which differ by only 29% in R_s . This is the pair that stresses HLR 2's $\pm 10\%$ repeatability requirement, so it's the one worth analyzing rather than copper vs. steel, which differ by over 15 $\times$.

A sample loads the sensing coil by adding a reflected resistance ΔR proportional to R_s (through the mutual coupling and coil geometry, here represented by a factor K). Using illustrative coil parameters – $K \approx 400$, self-inductance $L = 10 \mu\text{H}$, self-resistance $R_0 = 1 \Omega$ (to be replaced with values measured from the built coil) – the coil impedance magnitude is:

$$|Z| = \sqrt{(R_0^2 + (2\pi fL)^2)}$$

At 60 kHz, $|Z| \approx 3.90 \Omega$, giving:

Material	ΔR (60 kHz)	Phase shift
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Copper	25.6 mΩ	0.376°
Aluminum	38.9 mΩ	0.572°
Brass	50.3 mΩ	0.738°

The aluminum–brass difference is 11.3 mΩ, or 0.166° of phase.

Noise budget: Requirement 2.3.2, R4 specifies $\pm 10\%$ repeatability (treated here as a 3σ spec, so $\sigma \approx 3.3\%$ of the mean). For aluminum, that gives $\sigma_R \approx 1.30$ mΩ, or 0.019° of phase noise. The aluminum–brass separation is therefore:

$$0.166^\circ / 0.019^\circ \approx 8.7 \text{ pooled standard deviations}$$

This clears the 6σ separation target in requirement 2.3.2, R3 with margin, and every other material pair separates by more (12–19 σ). The same calculation at 240 kHz gives 8.7σ as well, so both excitation frequencies support the classifier. ADC quantization noise (STM32 12-bit ADC [2], ~960 samples per 2 ms acquisition window) works out to about 0.0006°, about 300 times smaller than the aluminum–brass signal. Repeatability is the limiting noise source rather than quantization.

2.4.3 Confound: coil temperature drift

Copper magnet wire has a temperature coefficient of resistance of about 0.393%/°C [8]. Applied to the coil's self-resistance R_0 , this drift competes directly with the aluminum–brass separation margin:

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

Solving for the temperature change that would consume the entire aluminum σ_R budget (1.30 mΩ at 60 kHz) gives $\Delta T \approx 0.33^\circ\text{C}$. This is a small margin: a coil warmed by ambient conditions, solenoid heat, or self-heating during repeated trials could drift by this much within a single test session, which would silently degrade repeatability. This is the justification for requirement 2.3.2, R5 (empty-platform baseline at power-up, on request, and after a temperature-triggered prompt) — without periodic re-baselining, thermal drift alone could erode the classification margin shown above.

2.4.4 Secondary risk: dielectric channel

The acrylic/HDPE pair is a harder separation problem and worth flagging even though the eddy-current path is the primary risk analyzed above. Modeling the sensor as a parallel-plate capacitor with an FR4 cover layer ($\epsilon_r \approx 4.4$) in series with the sample, the effective permittivity is roughly the average of the two:

$$\epsilon_{\text{eff}} \approx (\epsilon_{\text{cover}} + \epsilon_{\text{sample}}) / 2$$

This gives $\epsilon_{\text{eff}} \approx 3.55$ for acrylic ($\epsilon_r \approx 2.7$) and $\epsilon_{\text{eff}} \approx 3.35$ for HDPE ($\epsilon_r \approx 2.3$) which is only a 6% difference between the two materials, versus roughly 24-32% change from the no-sample baseline. This confirms that baseline subtraction (2.3.3, R6) is doing most of the work in this channel, and that acrylic/HDPE separation deserves its own characterization pass once electrodes are built, since 6% is a much tighter margin than the 29% seen in the aluminum–brass eddy-current case.

3. Ethics, Safety, and Societal Impact

MaterialID is designed as a material-classification aid and is not intended to replace certified composition-testing equipment.

The IEEE Code of Ethics commits engineers to hold paramount the safety and welfare of the public [1]. A misclassification becomes a safety concern if a user relies on the result when selecting material for a safety-critical application. The device returns "UNKNOWN" whenever measured properties do not sufficiently match a calibrated class (2.3.5, R5) rather than forcing a guess. The Code also commits engineers to honest, realistic reporting of results [1]. This is why the OLED reports a confidence value alongside the prediction, and why documentation will state the calibrated material set and its limits rather than implying general-purpose identification.

The clearest misuse risk is a hazardous or restricted material being misread as a benign one. Magnesium, which is flammable in machining, or beryllium-copper, which carries a toxic dust hazard, could be misclassified as aluminum or copper if they fall outside the six calibrated classes. This is the case the UNKNOWN threshold is meant to catch: an out-of-set material should fail to match any calibrated class closely enough to be classified (2.3.5, R5).

Documentation will state that MaterialID should not be used as the sole verification method for materials in safety-critical applications such as aerospace structures, medical equipment, pressure vessels, or load-bearing structural systems, and should not be relied on to screen for hazardous or regulated materials.

The design will follow IEC 62368-1 for equipment safety and FCC 47 CFR Part 15, Subpart B for unintentional radiated emissions, since the system's clock and excitation circuitry operate above the 9 kHz threshold that triggers this regulation. PCB design and assembly will follow IPC-2221 and IPC-A-610. Component and solder selection will follow RoHS restricted-substance limits as a design practice, even though the project is not sold commercially and RoHS does not apply as a legal requirement. Soldering, PCB assembly, and powered debugging will follow ECE 445 laboratory safety procedures and campus EHS policy [7].

The device operates from a low-voltage external power supply, which limits shock risk. The primary electrical hazard is the inductive transient generated by the solenoid. A flyback diode and appropriately rated switching components (2.3.4, R2) prevent this transient from damaging the electronics or presenting a hazard in a fault condition. The solenoid is a moving mechanical component. It will be located beneath the sensing platform and enclosed so the user cannot place a finger in the mechanism during normal operation. Repeated actuation may cause localized heating in the solenoid coil, so the enclosure will keep externally accessible surfaces within a safe touch-temperature limit during continuous testing.

Unidentified material stock is often discarded because users cannot confidently determine what it is. A low-cost preliminary identification tool could let more leftover material be reused rather than discarded, benefiting machine shops, makerspaces, and teaching labs that would otherwise default to expensive XRF analysis or outright disposal.

The project has minimal privacy concerns. MaterialID does not require user accounts, cameras, cloud connectivity, or the collection of personal information. If a microphone is used for mechanical sensing, its samples are only used during the short controlled ring-down measurement and do not need to be permanently stored.

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