



Non-Destructive Multi-Sensor Fusion Based Gold Purity Estimation Using Embedded Machine Learning

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DOI: 10.5281/zenodo.19558880

ABSTRACT

Gold purity testing is an essential requirement in the jewellery industry to ensure transparency, maintain customer trust, and comply with quality standards. Traditional testing techniques such as the fire assay method provide highly precise measurements but require destructive chemical analysis, which damages the sample being tested. Modern laboratory methods like Energy Dispersive X-Ray Fluorescence (ED-XRF) enable non-destructive elemental analysis; however, these systems are expensive and generally limited to specialized laboratories.

This research proposes a portable and economical gold purity estimation system based on multi-sensor data fusion and embedded machine learning techniques. The system integrates multiple sensing mechanisms, including mass measurement using a load cell, dimensional analysis for volume calculation, and electrical conductivity detection through an eddy current sensing coil. Data collected from these sensors are processed using an ESP32 microcontroller, which performs feature extraction and executes a lightweight regression-based machine learning model to estimate gold purity in parts per thousand.

Unlike traditional single-parameter testing devices, the proposed system combines multiple physical parameters to improve prediction reliability. The fusion of density, conductivity, and dimensional information allows the system to better identify variations in alloy composition. The machine learning model is trained using certified gold samples ranging from 14 karat to 24 karat, and its performance is evaluated using standard metrics such as Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and coefficient of determination.

The proposed framework focuses on developing a low-cost, fast, and environmentally friendly testing solution that can be used directly in jewellery shops and small retail environments. The device is designed to deliver rapid purity estimation within a few seconds without damaging the sample. Although hardware prototype development is currently in progress, theoretical analysis suggests that the proposed multi-sensor system could achieve an estimated prediction accuracy of 90–95%, demonstrating its potential as an alternative to expensive laboratory-based gold testing systems.

Keywords:- Non-Destructive Testing, Gold Purity Estimation, Sensor Fusion, Embedded Machine Learning, Eddy Current Sensor, ESP32.

1. INTRODUCTION

Gold is one of the most valuable precious metals and is widely used in jewellery and financial investments across the world. In countries such as India, gold jewellery holds both cultural and economic significance. Because of this importance, accurate determination of gold purity is essential to protect consumers and maintain transparency within the jewellery market.

According to the Bureau of Indian Standards (BIS), gold purity is generally expressed in karats (K) or parts per thousand (ppt). Traditional methods such as the Fire Assay technique provide precise measurements but require the destruction of a portion of the sample during chemical analysis. Although this technique is highly reliable, it is time-consuming and involves the use of hazardous chemicals.

Another commonly used method is Energy Dispersive X-Ray Fluorescence (ED-XRF), which enables non-destructive elemental analysis. However, the cost of XRF equipment and the requirement for specialized laboratories limit its accessibility, especially for small jewellery businesses.

Therefore, there is a growing demand for a portable, low-cost, and non-destructive method capable of estimating gold purity quickly and reliably. Advances in embedded electronics, sensor technology, and machine learning have created opportunities to develop such systems.

1.1 Existing Testing Techniques



Several methods are currently used for determining gold purity. Each technique has its own advantages and limitations.

Fire Assay Method : The Fire Assay technique is considered one of the most accurate methods for gold analysis. However, it requires chemical processing and destroys the tested sample during the procedure.

ED-XRF Testing: Energy Dispersive X-Ray Fluorescence allows non-destructive elemental analysis and is widely used in professional testing laboratories. Despite its accuracy, the equipment cost is high and requires trained operators.

Density-Based Testing: Density measurement methods estimate purity based on the relationship between mass and volume. Although simple to implement, density alone may not provide reliable results for jewellery alloys containing different metals.

Conductivity-Based Testing: Electrical conductivity measurements can provide information about metal composition. However, variations in alloy composition may affect measurement accuracy. Most existing portable devices rely on a single sensing parameter, which may lead to inaccurate results when dealing with complex alloy compositions.

1.2 Identified Research Gap

Many existing gold testing methods require laboratory infrastructure and trained personnel, making them unsuitable for rapid testing in local jewellery shops. Small retailers often depend on external laboratories, resulting in additional costs and delays.

Furthermore, most low-cost testing devices rely on only one physical parameter, such as density or electrical conductivity. This limitation reduces reliability because different alloy combinations may produce similar readings.

Limited research has explored the integration of multiple sensing techniques combined with embedded machine learning models for gold purity estimation. A multi-sensor fusion approach that combines density, dimensional measurement, and conductivity analysis can potentially improve prediction accuracy without significantly increasing system cost.

1.3 Objectives of Proposed Work

The main objectives of this research are:

- To design a non-destructive gold purity estimation system
- To integrate density, dimensional, and conductivity sensing techniques
- To implement a machine learning model on an ESP32 microcontroller
- To develop a portable and cost-effective prototype
- To evaluate the performance of a regression-based purity prediction model

2. PROPOSED SYSTEM ARCHITECTURE



Fig -1: PROPOSED SYSTEM ARCHITECTURE

The proposed system consists of multiple sensing modules integrated with an embedded processing unit. The overall architecture includes five primary stages: sensing, signal conditioning, feature extraction, machine learning prediction, and output display.

The hardware components used in the system include:

- Load cell with HX711 module for mass measurement
- Dimensional measurement module for volume estimation
- Eddy current sensing coil for electrical conductivity detection
- ESP32 microcontroller for data processing and ML inference
- LCD display for presenting purity results

The sensor outputs are digitized and processed by the ESP32 controller. The extracted features are then used as input for a regression-based machine learning model, which estimates gold purity in parts per thousand.

2.1 Mathematical Modeling

Density Estimation



Density is calculated using the relationship:

$$\rho = \text{Mass} / \text{Volume}$$

Where:

$$\rho = \text{Density (g/cm}^3\text{)}$$

Pure gold has a density of approximately **19.32 g/cm³** at room temperature. When gold is alloyed with metals such as copper or silver, the overall density decreases. Therefore, density can be used as a useful indicator of purity.

Conductivity Modeling

Electrical conductivity is defined as:

$$\sigma = 1 / \rho_e$$

Where:

σ = Electrical conductivity

ρ_e = Electrical resistivity

In eddy current sensing, the impedance of the sensing coil can be expressed as:

$$Z = R + j\omega L$$

Where:

Z = Impedance

R = Resistance

ω = Angular frequency

L = Inductance

Changes in alloy composition influence conductivity and magnetic response, which in turn affect the impedance of the coil.

- **Regression Model**

The predicted purity is calculated using a regression model:

$$\text{Purity} = a_1(\text{Density}) + a_2(\text{Conductivity}) + a_3(\text{Dimension}) + c$$

Where:

a_1, a_2, a_3 = regression coefficients

c = bias constant

These coefficients are obtained during supervised machine learning training.

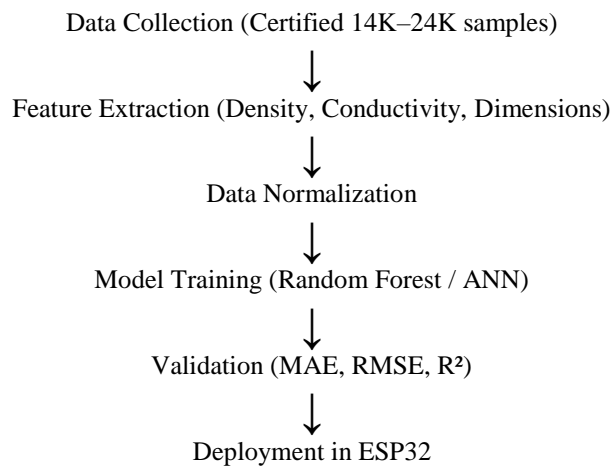
Table -1: Karat Value v/s Theoretical Density

Karat	Expected Density (g/cm ³)
24K	19.32
22K	17.5 - 18.5
18K	15 - 16
14K	13 - 14

- **The decrease in density validates its importance as a predictive feature.**

2.2 Machine Learning Framework

The proposed embedded ML workflow includes:



Expected accuracy (literature-based modeling): 90–95%



3. IMPLEMENTATION METHODOLOGY

The hardware implementation includes the following components: ESP32 microcontroller, HX711 24-bit ADC module, 5 kg load cell, Eddy current sensing coil, Dimensional measurement module, 16×2 LCD display, Regulated power supply

Signal Processing Steps: Sensing, Signal conditioning, Feature extraction, Machine learning prediction, Output display.

3.1 Advantages of Proposed System

- Non-destructive testing, Portable device architecture, Lower cost compared to ED-XRF systems, Environmentally friendly operation, Rapid testing results, Suitable for jewellery shop applications

3.2 Limitation of Proposed System

- Requires accurate calibration, Surface plating may influence measurements, Limited penetration depth for conductivity sensing, Prediction accuracy depends on dataset quality

4. THEORETICAL ANALYSIS AND EXPECTED PERFORMANCE

Since prototype fabrication is under development, theoretical modeling and literature-backed analysis have been conducted.

Expected System Performance:

Parameters	Expected Value
MAE	< 5 ppt
RMSE	< 7 ppt
Accuracy	90–95%
Testing Time	< 10 seconds

Sensor fusion is expected to reduce prediction error compared to single-parameter systems.

5. FUTURE WORK

- Prototype fabrication and hardware testing
- Calibration using BIS-certified samples
- Large dataset creation (minimum 100 samples)
- Comparative validation with ED-XRF systems
- Mobile application integration
- Optimization of regression model

6. CONCLUSIONS

This study presents the design framework of a portable non-destructive gold purity estimation system based on multi-sensor fusion and embedded machine learning. By combining density measurement and conductivity analysis, the system aims to improve purity prediction accuracy compared to single-sensor approaches.

The proposed architecture emphasizes affordability, portability, and environmentally friendly operation. These features make it suitable for small jewellery businesses and rapid screening applications. Although experimental validation will be performed after prototype development, the theoretical analysis suggests promising potential for practical implementation.

7. ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to the faculty members of Siddhivinayak Technical Campus, Maharashtra, for their guidance and support during the development of this research work. Special thanks are extended to the Electronics and Telecommunication department for providing technical insights and encouragement throughout the study. The authors also acknowledge the valuable suggestions provided during the conceptualization of the proposed system architecture.

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