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CONCEPTUAL MODELLING OF GOLD AUTHENTICATION SYSTEM BASED ON ULTRASOUND PROPAGATION ANALYSIS

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Abstract— This paper presents a simulation-based study of a non-destructive gold authentication system using ultrasonic wave propagation analysis. The system is developed and simulated in Visual Studio Code using Python-based tools. Simulation data is obtained from COMSOL Multiphysics, utilizing a 5 MHz ultrasonic sensor. The total acoustic pressure (Pa) is extracted as a key feature for statistical analysis, employing metrics such as Mean Squared Error (MSE), Root Mean Squared

Method, Ultrasonic, Acoustics Pressure, MSE, RMSE, Correlation

Error (RMSE), and Correlation Coefficient. Gold purity classification is performed through comparative analysis between data from pure gold and gold alloyed with tungsten or silver. The results demonstrate high accuracy in purity identification and highlight the potential of the proposed system for practical real-time applications.

I. Introduction

The authentication of gold is crucial in industries such as jewellery, finance and cultural heritage. As the price of gold increase, the risk of fraud also increases but the conventional methods for gold authentication: visual inspection, chemical tests [1] and fire assay [2] are invasive, time-consuming and prone to errors and fraud. This method also has limitation regarding accuracy, reliability, invasiveness and cost [3-4]. To solve this problem, a reliable, non-destructive and accurate authentication system using ultrasound has been proposed in this research. Ultrasound can help identify internal inconsistencies, voids, cracks and inclusions that indicate impurities or counterfeit products in authentication process. In addition, ultrasound imaging is non-destructive, allowing for the examination of gold without damaging the sample. It provides real-time imaging and can penetrate through various depth, offering detailed internal insights [5]. In term of material properties gold has unique ultrasonic properties, which include high acoustic impedance and sound speed, making it practical in ultrasonic imaging and material characterization [6]. Moreover, gold has high density (19.32 g/cm^3) and low stiffness, leading to high acoustic impedance, which is beneficial in acoustic coupling and enhancing ultrasonic signals. The speed of sound in gold-approximately 3240 m/s [7], also can be use as parameter for gold purity authentication due to its consistency and measurable value. Furthermore, gold also shows low ultrasonic attenuation, making it ideal for high-frequency applications where signal clarity is crucial [8].

This research proposes a conceptual model for a gold authentication system that utilizes ultrasound technology to enhance accuracy, reliability, and non-destructive testing capabilities. The study is guided by three main objectives. The first objective is to develop a simulation model for an ultrasonic gold authentication system using Python. The second objective involves analyzing and comparing reference data from pure gold with data from gold mixed with tungsten and silver. The final objective is to validate the system through comprehensive statistical analysis.

The methodology includes a detailed investigation of the ultrasonic properties of gold, the development of mathematical models, and the implementation of simulations in Python. Data analysis is also conducted in Python using various statistical methods, including Mean Squared Error (MSE), Root Mean Squared Error (RMSE), and Correlation Coefficient. Specifically, MSE is employed to quantify the average squared difference between theoretical and experimental values, serving as an indicator of model accuracy.

In recent studies, the MSE has been widely used to evaluate the performance of machine learning models in ultrasonic flaw detection [9]. These studies concluded that models with lower MSE values yield more accurate and reliable predictions of material defects. Similarly, the RMSE, which is the square root of the average squared differences between predicted and actual values, has been applied in various ultrasonic testing scenarios. Zhao et al. utilized RMSE to assess the consistency of ultrasonic signals in concrete structure evaluations [10], while Lari et al. employed it to evaluate the accuracy of AI models in estimating defect sizes from ultrasonic data [11]. Both studies demonstrated that lower RMSE values correspond to higher model reliability and predictive accuracy.

Finally, the Correlation Coefficient is employed to measure the similarity between two ultrasonic signals, typically by comparing a test signal with a reference or ideal signal [12]. This statistical approach enables rigorous assessment while maintaining the non-destructive nature of testing. Collectively, these methods offer significant potential benefits for the jewellery industry, financial markets, and cultural heritage preservation by ensuring the authenticity and integrity of precious materials.

II. Methodology

A. Data Acquisition

For the data used in this research which is the total acoustic pressure (Pa) data, it has been obtained from simulations conducted in COMSOL Multiphysics. These simulations modelled ultrasonic wave propagation through three types of materials which are:

- Pure gold
- Gold mixed with tungsten
- Gold mixed with silver

The dataset produced from each simulation consist of acoustic pressure (Pa) values recorded over uniform time intervals. This data is saved in Excel format, with two column which is time (s) and total acoustic pressure (Pa). This format makes it easier to be use as input for signal processing and analysis in Python.

B. Signal Processing in Python

Phyton is a high-level, interpreted programming language known for its simplicity, flexibility and rich libraries which is useful in signal processing and data analysis. This programming language is accessible even to person without strong programming background which can help the researcher focus more on interpreting data rather than writing complex code. Moreover, python also support libraries that has been used in this research for statistical analysis such as:

- **Pandas**: to load and organize Excel data
- **NumPy**: for numerical and statistical computation

- **matplotlib**: for waveform visualization

These libraries enable the user to perform everything from basic descriptive statistics to advanced regression modelling. In a study by Mckinney, he introduced the Pandas library capabilities in data analysis [13]. This library brought R-like data frame structures to Python, simplifying tasks such as data cleaning, transformation, and statistical summary. Mckinney also mentioned this library helps in producing efficient data structures for handling labelled heterogeneous datasets which is a core in statistical method. Moreover, library like NumPy form the core of Python's statistical ecosystem and support a wide array of data manipulation tasks which can produced efficient numerical and statistical operations [14]. Additionally, matplotlib library has been introduced in study by hunter which shows that matplotlib is capable of plotting 2D graph for data representation [15]. Visualization is crucial for conducting data analysis and communicating statistical result effectively.

C. Statistical Analysis

Statistical analysis is integrated into this simulation to help in determining the purity of gold. For each test signal, the following metrics were computed with respect to the pure gold reference which is MSE as shown in Equation (1) to quantifies average squared difference, RMSE as shown in Equation (2) to interprets signal deviation magnitude and Correlation Coefficient *(r)* as shown in Equation (3) to measures signal similarity.

$$\boldsymbol{MSE} = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \quad (1)$$

$$\boldsymbol{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \quad (2)$$

$$\boldsymbol{r} = \frac{\sum(y_i - \bar{y})(\hat{y}_i - \bar{\hat{y}})}{\sqrt{\sum(y_i - \bar{y})^2 \sum(\hat{y}_i - \bar{\hat{y}})^2}} \quad (3)$$

where:

n = Total number of data samples

y_i = Measured value

$\hat{y}_i$ = Reference value

$\bar{y}$ = Mean of measured value

$\bar{\hat{y}}$ = Mean of reference value

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Figure 1 illustrates the process of determining gold purity using statistical analysis.

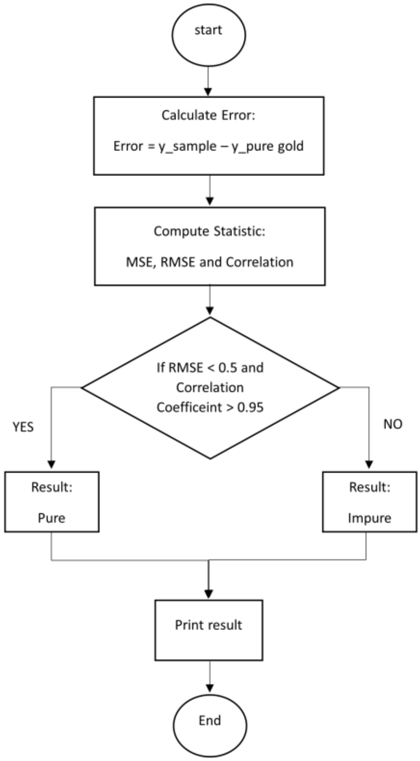

Figure 1: Flowchart for Statistical Analysis

The procedure begins by calculating the difference between the received ultrasonic signal and the reference signal. Subsequently, the statistical parameters described earlier are computed. If the correlation coefficient exceeds 0.95 and the RMSE is less than 0.5, the signal is deemed accurate, and the sample is classified as pure. Otherwise, it is labelled as impure. Finally, the system outputs the classification result along with the computed statistical values, thereby completing the analysis.

III. Results and Discussion

Figure 2 presents the simulated ultrasonic waveforms for gold mixed with tungsten and gold mixed with silver. These waveforms were visualized using Python's matplotlib library for clearer analysis.

The acoustic behaviour differs significantly based on the material composition. Gold mixed with tungsten demonstrates a waveform with steeper peaks and higher-pressure levels due to tungsten's higher acoustic velocity (5220 m/s) and comparable density (19.5 g/cm³) to gold. This mismatch in acoustic impedance causes stronger reflections, in line with studies highlighting enhanced wave propagation in tungsten-based alloys [16].

Conversely, the waveform for gold mixed with silver is

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smoother and has reduced pressure intensity. This is attributed to silver's lower density and slightly higher speed of sound compared to gold, leading to a smaller impedance mismatch. Consequently, sound waves undergo less reflection and more attenuation, which reduces signal amplitude, a behaviour consistent with known properties of silver alloys [17].

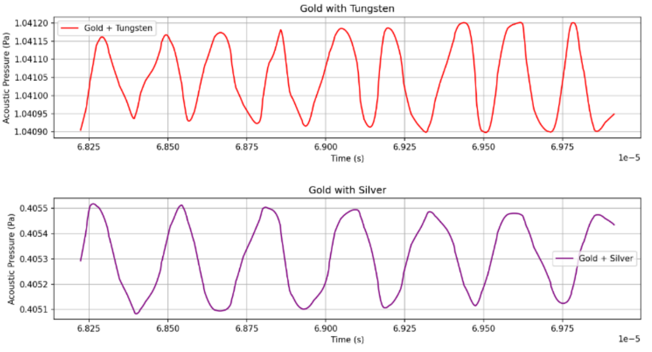

Figure 2: Graph for Gold mixed with Tungsten and Silver

In summary, the tungsten-gold mixture is more distinguishable due to its prominent ultrasonic signature, which features sharper peaks, higher acoustic pressure, and greater reflection intensity. These characteristics result from tungsten's significantly different acoustic properties especially its higher sound velocity and similar density which create a large acoustic impedance mismatch with gold. This mismatch amplifies wave reflection and preserves the waveform's energy, making it easier to differentiate from pure gold using both visual and statistical analysis.

In contrast, the silver-gold mixture presents a more subtle challenge. Silver's acoustic properties are closer to those of gold, particularly in terms of impedance. As a result, the ultrasonic waveforms appear smoother and show reduced pressure variation, which diminishes the distinguishability from pure gold. This subtle difference requires a more sensitive detection system and robust analytical methods to ensure reliable classification. Hence, while the ultrasonic method shows strong potential, its sensitivity must be carefully calibrated to ensure accurate impurity detection across different alloy types.

To further validate the observed waveform differences, a statistical analysis was conducted to quantify the similarity between the test samples and pure gold reference signals. As shown in Table 1, the RMSE value for gold mixed with tungsten is within the acceptable threshold (< 0.5), but the correlation coefficient is significantly low, indicating poor similarity to the pure gold reference. Thus, it is classified as impure. Similarly, the silver mixture exceeds the RMSE threshold and exhibits a negative correlation, reinforcing its classification as impure.

Table 1: Statistical Analysis Summary

Material	MSE	RMSE	Correlation Coefficient	Purity
Gold with Tungsten	0.047495	0.217934	0.015125	IMPURE GOLD
Gold with Silver	0.728752	0.853670	-0.075788	IMPURE GOLD

The results confirm the effectiveness of ultrasound-based methods in identifying gold impurities. Distinct waveform patterns and statistical deviations indicate that ultrasonic responses vary according to material composition. The low correlation and high RMSE values in both alloy samples provide reliable indicators of impurity. This approach shows promise in controlled environments. However, deploying it in real-world settings would require accounting for factors like ambient noise, temperature variability, and imperfect sensor coupling.

IV. Conclusion

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This study successfully demonstrates the feasibility of using ultrasonic wave analysis combined with Python-based statistical evaluation for non-destructive gold authentication. By simulating ultrasonic wave propagation in pure and impure gold (with tungsten and silver), the system was able to reveal distinctive acoustic patterns linked to material composition. The statistical metrics MSE, RMSE, and correlation coefficient, further validated these differences and enabled effective classification. The approach is practical, low-cost, and highly adaptable for real-time implementation, and its simplicity makes it accessible to broader applications, including the jewellery industry, quality assurance, and anti-counterfeit efforts.

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