# Final Project Report: IoT-Ready Microwave-based Smart Coatings for Real-Time Coating Damage Detection

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***Abstract*—Advancements in wireless microwave sensor, artificial intelligence, and augmented reality have paved the way for next-generation structural health monitoring solutions. This report presents the design, implementation, and experimental validation of a microwave-based coating health monitoring system, focusing on improved detection precision, and enhanced spatial localization through the integration of differential and multi-resonant sensor architectures. The outcome of the research advances microwave-based non-destructive testing for real-time, passive, and robust coating health monitoring in aerospace, marine, and civil infrastructure applications. This work was supported in part by the IEEE MTT-S Graduate Fellowship.**

***Index Terms*—Microwave Sensors, Smart Coating, Split Ring Resonator, Wear Detection, Microwave NDT, Industrial IoT, Augmented Reality, Real-time Sensing.**

## I. INTRODUCTION

THE global challenge in monitoring the health and the integrity of structures including bridges, airplanes, pipelines, and turbines, have prompted the need for developing robust, scalable, and real-time non-destructive testing (NDT) mechanisms. Current methods, including ultrasonic testing, eddy current inspection, and visual assessments, are predominantly probe-based, manual, and conducted at scheduled intervals rather than in real time. However, wear in these structures occur unpredictably due to environmental and operational stresses, making periodic inspections insufficient. To ensure early detection and prevent structural failures, real-time monitoring solutions are essential for continuous assessment, damage detection, and maintenance.

To achieve real-time monitoring, the sensor must be integrated with the structure or the coating layer, requiring it to be low-profile and planar. Microwave-based frequency selective surface (FSS) sensors present the optimal solution due to their compatibility with these requirements [1], [2], [3], [4]. FSS sensors are passive devices that detect coating damage through electromagnetic interaction with the coating material, where changes in both the coating's thickness and permittivity cause shifts in the resonant frequency, indicating wear or degradation. However, a limitation of conventional FSS sensors is that all elements resonate at the same frequency, making it challenging to locate the exact region of damage. This report addresses two approaches: one utilizing post-processing techniques for wear localization, and the other employing a multi-resonant architecture to overcome this limitation without relying on post-processing.

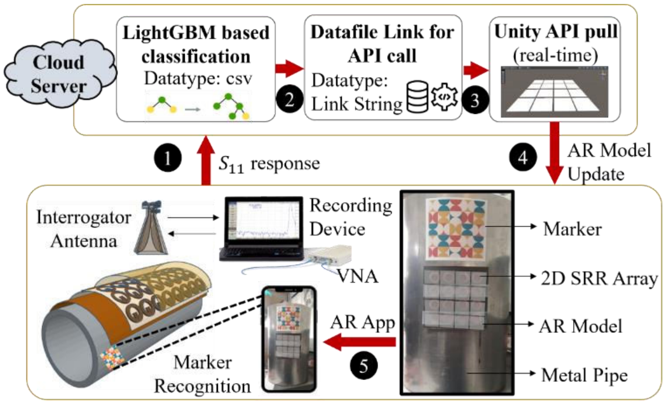

Fig. 1. Process workflow of the proposed system which includes data acquisition from the passive 2D SRR array using an interrogator antenna connected to a VNA and sent to the cloud server for coating damage localization and augmented reality-based visualization.

## II. DEVELOPED SOLUTION AND RESULTS

The first version of the developed solution consists of a microwave-based smart coating system utilizing a passive 2-D split ring resonator (SRR) array, designed to monitor the wear of coatings in real time. This system leverages the resonant frequency changes in the SRR array, which are caused by variations in the coating's thickness and material properties due to wear. To improve the localization of wear, the system incorporates AI-based post-processing techniques, enabling accurate identification of damaged regions across large surfaces. Moreover, a cloud-based augmented reality (AR) platform is integrated to offer enhanced visualization of the wear pattern, allowing out-of-sight and real-time monitoring, which facilitates faster and more intuitive decision-making in industrial environments (Fig. 1) [5], [6].

The results demonstrate that the SRR-based system accurately detects coating wear through both mechanical and chemical erosion processes. In mechanical erosion, the system exhibited an increase in resonant frequency as the coating thickness was reduced, with an average increase of ~61 MHz for 0.1 mm loss in coating thickness. Similarly, chemical erosion tests demonstrated an increase in resonant frequency

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as the coating dissolved, confirming the system's sensitivity to both types of wear. The integration of AI for wear localization was evaluated using a supervised machine learning model, achieving a classification accuracy of over 99%, precision close to 1.0, and recall exceeding 80%. Additionally, the AR-enabled visualization tool proved effective in displaying the wear patterns, with minimal alignment errors (~0.55 cm), ensuring accurate and reliable representation of the coating's health status (Fig. 2).

The second approach focused on a multi-resonant FSS sensor designed for precise spatial localization of coating wear, without the need for post-processing. The sensor contained two regions of 10x10 nested square patch resonators, resonating at 4.5 GHz and 5 GHz, respectively. Wear tests conducted on a 225 µm PVC coating demonstrated the system's ability to localize coating damage with high accuracy. The system exhibited frequency shifts of ~231 MHz, with a sensitivity of 70 MHz per 75 µm of wear (Fig. 3).

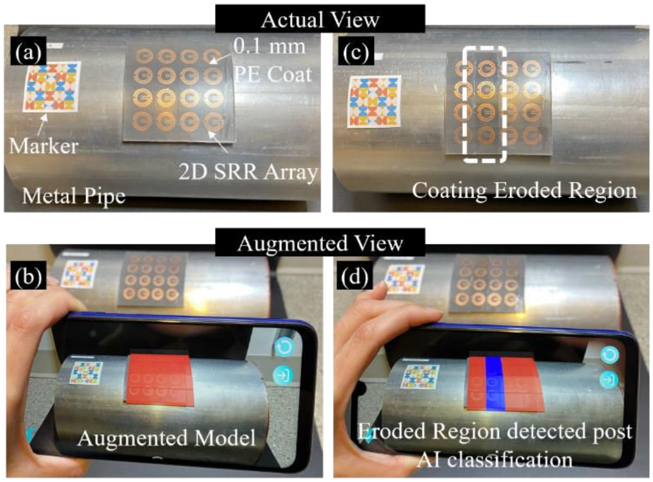

Fig. 2. Working of the custom-built AR Android application where the coating eroded region is detected, marked, and visually augmented over the 2D SRR array.

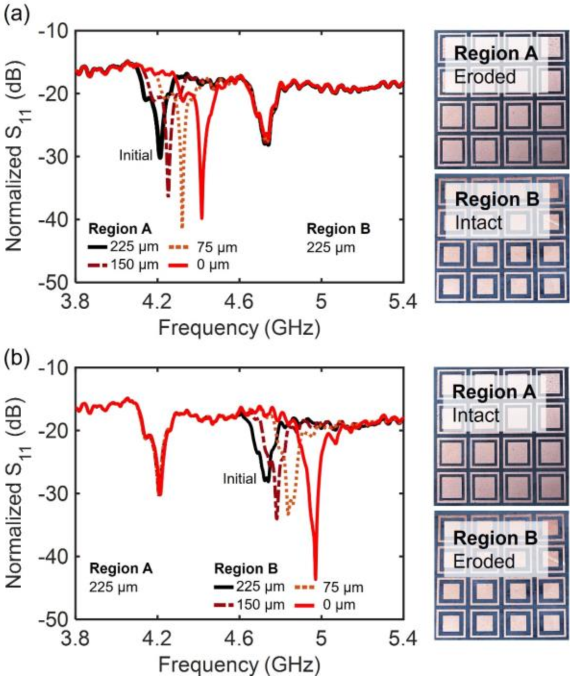

Fig. 3. (a) Normalized $S_{11}$ response of the FSS sensor when the coating over region A was eroded while region B coating was intact, and (b) Normalized $S_{11}$ response of the FSS sensor when the coating over region B was eroded while region A coating was intact.

## III. CONCLUSION

In conclusion, both the developed systems were capable of detecting and localizing the region of coating damage with high sensitivity. By integrating passive SRR sensors with AI-driven wear localization and augmented reality, the system provides accurate, scalable, and robust monitoring solutions for diverse applications, including aerospace, marine, and infrastructure. While this work has made significant advancements in microwave-based non-destructive testing for coating health monitoring, several areas remain unexplored, opening opportunities for future research. A key limitation of FSS-based sensors is the need for a dielectric substrate. Future research should explore substrate-less designs, integrating SRRs directly into coatings, using conductive inks for printing.

## IV. IMPACT OF FELLOWSHIP, AND CAREER PLAN

I would like to express my sincere gratitude to MTT-S and IEEE for their unwavering support and investment in my research journey, as well as for their encouragement of all the graduate fellows. As I approach the completion of my PhD, which has been full of invaluable experiences, including attending IMS, and even winning the 3MT®, I am excited to pursue a career in academia. My goal is to become a professor, but with an entrepreneurial touch, where I can contribute to advancing the fields of microwave sensing, smart materials, and real-time monitoring technologies.

## REFERENCES

[1] V. Balasubramanian, O. Niksan, M. C. Jain, K. Golovin, and M. H. Zarifi, "Non-destructive erosive wear monitoring of multi-layer coatings using AI-enabled differential split ring resonator based system," *Nat. Commun. 2023 141*, vol. 14, no. 1, pp. 1–12, Aug. 2023, doi: 10.1038/s41467-023-40636-9.

[2] V. Balasubramanian, M. C. Jain, K. Golovin, and M. H. Zarifi, "Real-time Non-Destructive Erosion Monitoring of Coatings using Passive Microwave Split Ring Resonator Sensor," *2023 IEEE Int. Conf. Consum. Electron.*, pp. 01–04, Jan. 2023, doi: 10.1109/ICCE56470.2023.10043427.

[3] A. M. J. Marindra and G. Y. Tian, "Chipless RFID sensor for corrosion characterization based on frequency selective surface and feature fusion," *Smart Mater. Struct.*, vol. 29, no. 12, p. 125010, Oct. 2020, doi: 10.1088/1361-665X/ABBFF4.

[4] F. Costa, S. Genovesi, A. Monorchio, and G. Manara, "Calibration method for periodic surface based chipless tags," *2014 IEEE RFID Technol. Appl. Conf. RFID-TA 2014*, pp. 78–81, Oct. 2014, doi: 10.1109/RFID-TA.2014.6934204.

[5] V. Balasubramanian and M. H. Zarifi, "Augmented Reality-Assisted Battery-Less Microwave-Based Sensors for Smart Health Monitoring of Coatings," *IEEE MTT-S Int. Microw. Symp. Dig.*, pp. 277–280, 2024, doi: 10.1109/IMS40175.2024.10600183.

[6] V. Balasubramanian, O. Niksan, M. C. Jain, K. Golovin, and M. H. Zarifi, "Augmented Reality-Enhanced Microwave-Based Wireless Monitoring System for Smart Coating Applications," *IEEE Trans. Microw. Theory Tech.*, 2024, doi: 10.1109/TMTT.2024.3403838.