COATL - Millimeter Wave RADAR Project Proposal

Team 4

Version 1.0

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Executive Summary

The *Millimeter-Wave RADAR for Assessing Green Coffee Quality* project aims to develop an innovative, non-destructive method for measuring the moisture content of green coffee beans. Accurate moisture measurement is critical for optimizing coffee roasting processes and preserving quality during storage. Current solutions, such as oven drying or capacitive moisture sensors, are either destructive or cost-prohibitive for widespread use.

To address these challenges, this project proposes leveraging the XM125 60 GHz millimeter-wave RADAR module, known for its sensitivity to moisture due to water's strong absorption properties at this frequency. The system will utilize time-of-flight RADAR technology to detect variations in dielectric properties influenced by moisture content. A key innovation of this approach is its potential to offer a low-cost, scalable alternative for producers, importers, and specialty roasters.

The project will result in a functional prototype comprising a RADAR-based sensor system, software to estimate dielectric constants, and a real-time graphical user interface for visualizing measurement data. Core deliverables include moisture content estimation software, validation against professional-grade sensors, and a user-friendly design for practical use.

This multidisciplinary effort will require expertise in RF system design, programming, CAD modeling, and data analysis. The project aligns with industry needs and has significant implications for improving coffee quality assessment methods while reducing costs for small-scale producers.

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1 Background and Research

Sponsor

The project is sponsored by the Coffee And Telesensing Lab (COATL), a research group focused on applying advanced sensing technologies to improve agricultural processes and product quality. COATL specializes in using state-of-the-art remote sensing techniques, including radar and microwave systems, to address challenges faced by coffee producers and processors. By combining expertise in electrical engineering, signal processing, and agricultural science, COATL aims to develop scalable, cost-effective solutions to enhance coffee quality monitoring and control.

Technology Domain and Context

The technology domain of this project is millimeter-wave radar sensing for agricultural product quality assessment. Specifically, this system uses the XM125 60 GHz pulsed coherent radar module to measure the moisture content of green coffee beans. Moisture content is critical in coffee's long-term storage stability, roasting profile, and overall quality. Traditional moisture measurement methods include oven drying (destructive and time-consuming) or capacitive sensors (non-destructive but expensive). The millimeter-wave radar system offers a promising alternative by leveraging water's strong absorption characteristics at 60 GHz. This approach has already been used for monitoring moisture in other agricultural products, such as drying leaves.

System Functionality

The radar-based moisture sensor works on a time-of-flight principle. The radar transmits a series of electromagnetic pulses and measures the delay and amplitude of reflected waves. When green coffee beans are placed in a sample holder, the dielectric properties of the beans—directly related to their water content—affect the reflected signal. By extracting the dielectric constant, the system estimates the moisture level in the sample. The relationship between reflectivity γ and permittivity is given by:

$$\gamma = \left(\frac{\sqrt{\epsilon_1} - \sqrt{\epsilon_2}}{\sqrt{\epsilon_1} + \sqrt{\epsilon_2}} \right)^2$$

where ϵ_1 and ϵ_2 are the relative permeabilities on either side of the coffee-air boundary.

A conceptual design of the proposed RADAR-based moisture sensor is illustrated in Figure 1 below. The system includes: (1) the XM125 radar module, (2) a sample holder designed to contain coffee beans, and (3) a corner reflector. When the sample holder is empty, the millimeter-wave pulses emitted by the radar are reflected back with high amplitude from the corner reflector. To minimize interference with the measurements, the sample holder must be made from materials transparent to 60 GHz waves. When filled with green coffee beans, the pulses are attenuated proportionally to the moisture content in the beans. The raw radar data from the XM125 module is processed using a computer or microcontroller to calculate the dielectric constant of the sample. The system's performance will be validated by comparing its moisture content estimates to those obtained using a commercial capacitive moisture sensor.

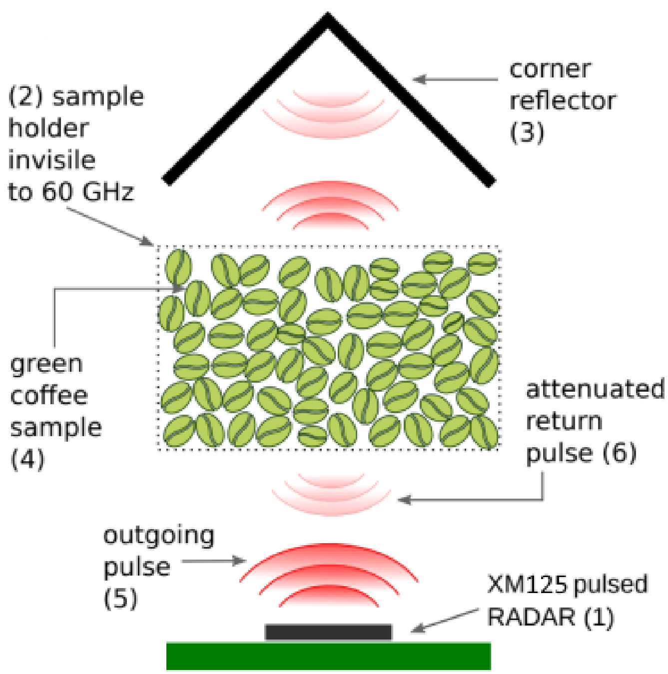

Figure 1: Conceptual model of material sensing with 60 GHz RADAR for coffee

1.1 Research

1.1.1 Commercial Off-the-Shelf Products

Our industry sponsor (Dr. Joshua Mendez) has provided us with the Acconeer XE125 EVK (evaluation board for the XM125 PCR module). Additionally, he's provided us with access to the RoastRite Coffee Moisture and Density Meter RM-800 to act as a known good test module/baseline for our test results.

1.1.2 Open Source Projects

We'll be using the Acconeer Exploration Tool (version A121) which runs on Python 3.11.9. Aside from using command line Python, we may utilize Spyder 6 for its convenience as a Python IDE. VS code will be used for C programming, along with the ESP-IDF.

1.1.3 Patents, Papers, White Papers, Articles, Conference Proceedings

Patents & White Papers:
Our project proposal and PDS have been thoroughly reviewed via extensive internet research to ensure that it does not infringe on any existing patents or intellectual property. We have conducted due diligence to confirm that all designs, methods, and materials used will be original or fall within the public domain.

Papers:

"A 60 GHz pulsed coherent radar for online monitoring of the withering condition of leaves," ScienceDirect, Jun. 16, 2022.
https://www.sciencedirect.com/science/article/pii/S0924424722003314 (accessed Jan. 2025).

T. Albing, R. Nelander, and Acconeer AB, "Material Classification of Recyclable Containers Using 60 GHz Radar," arxiv.org, 2023. https://arxiv.org/pdf/2312.14539

The two papers above use the same radar module as the one we will be using (the XM125). One detects moisture content in leaves, and the other detects recyclable material type. Neither is too dissimilar to our objective and appear to be good reference points. We plan to first try and replicate the recyclables project results to try and familiarize ourselves with the sensor, and periodically reference the leaf paper for any helpful information it may provide.

2 Product Design Specification

2.1 Product Overview

The millimeter-wave radar offers an affordable solution with capabilities rivaling more expensive competitors. This device accurately measures the moisture content of green coffee beans by sending a 60 GHz signal through the provided container. It helps users determine the freshness of their beans and whether it's time to discard or roast them. Designed for coffee enthusiasts and newcomers alike, the device ensures users can identify beans that are too dry or perfectly suited for roasting.

The device is simple to use: fill the container with the specified amount of coffee beans, ensuring it is not overfilled to maintain accuracy. Place the lid securely, then use the small screen to start the reading. Within moments, the moisture content will be displayed.

Initially, we will produce a limited quantity for our industry sponsor and as a proof of concept. If successful, we plan to pursue a patent and explore options for manufacturing or selling the finished product.

2.2 Stakeholders

Industry Sponsor

- Dr. Joshua Mendez

Engineering team

- Henry Sanders
- Chris Kane-Pardy
- Wallace McKenzie
- Kamal Smith

Customer/Intended Audience

- Coffee Roasters (companies)
- Coffee Enthusiasts

2.3 Requirements

- Must:
  - Be able to extract the dielectric constant of a fixed-volume sample placed in the RADAR's beam path for materials with dielectric constants ranging from 5-20.
  - Differentiate between at least 3 coffees with different moisture contents (e.g. 8%, 10%, and 12%)
  - Detect when the sample holder is empty.
- Should:
  - Be able to determine the moisture content of coffees in the range of 7%-15%.
  - Have the ability to determine the moisture content of green coffee with a resolution of 1%.
  - Provide estimates of moisture content that are within 20% of the value reported by a professional capacitive sensor moisture meter.
- May:
  - Have the ability to determine the moisture content of green coffee with a resolution of 0.1%.
  - Provide estimates of moisture content that are within 10% of the value reported by a professional capacitive sensor moisture meter.

2.4 Specifications

- XM125 PCR Module
- Acconeer A121 Exploration Tool

2.5 Initial Product Design

Hardware Architecture

L0 Block Diagram-

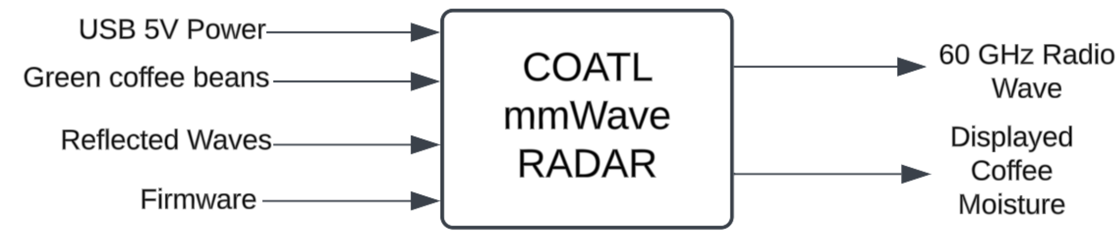

Figure 2: L0 Block Diagram - COATL mmWave RADAR

L1 Block Diagram-

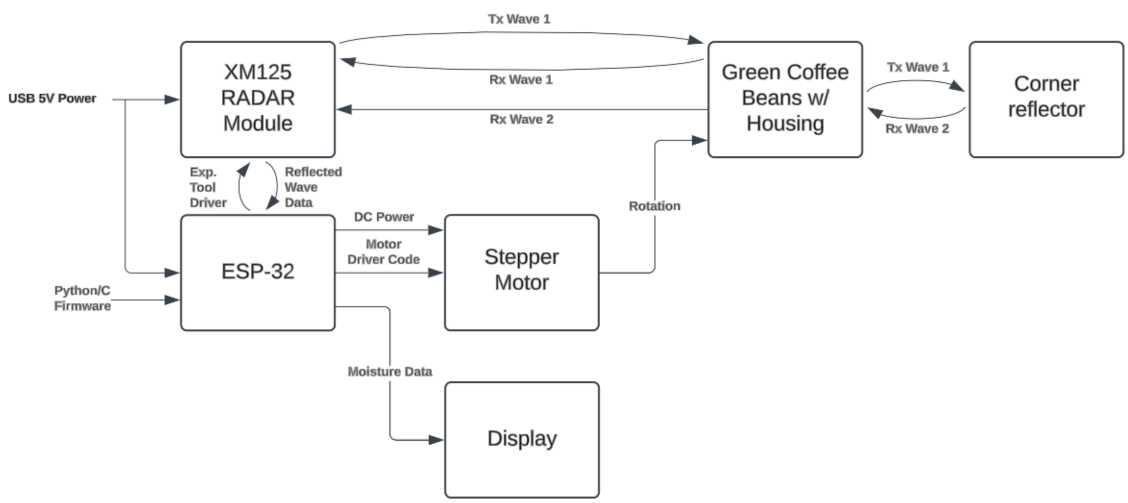

Figure 3: L1 Block Diagram - COATL mmWave RADAR

We intend to create L1 Block Diagrams for the individual modules in Figure 3 for the final revision of the project proposal.

Software Architecture

Languages-

- Python
- C (ESP-IDF)

IDE's-

- Spyder 6 (Python Scripting)
- VS Code (C Programming)
- STM32Cube Programmer (XE125 EVK Firmware Updates)

Data Flow-

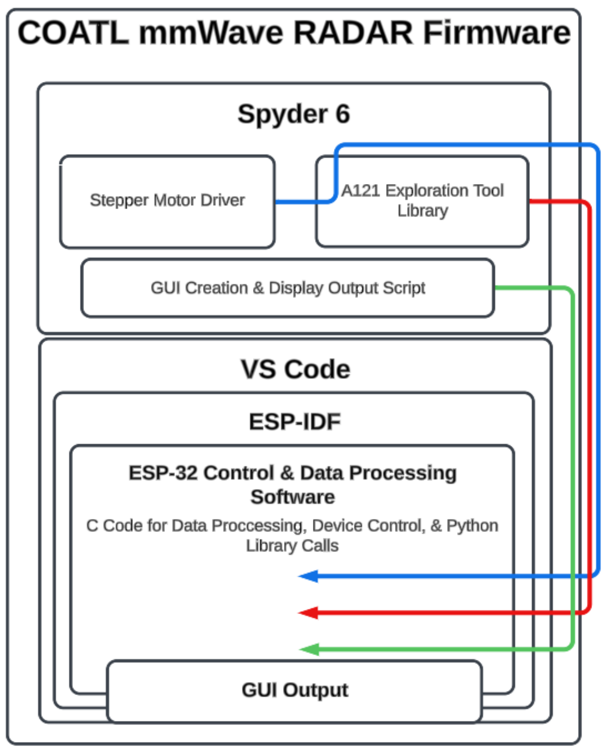

Figure 4: High-Level Data Flow Diagram

We intend to create more in-depth low-level code block diagrams for the final revision of the project proposal.

User interface/experience

- **Preparing for Measurement:** The user begins by placing the provided container on a flat surface and filling it with the required amount of green coffee beans, ensuring it is not overfilled to maintain measurement accuracy. The lid is securely placed, and the container is positioned in the designated slot of the RADAR system.
- **Initiating a Reading:** Through the UI, the user selects the "Start Measurement" option. The RADAR system sends a 60 GHz signal through the coffee beans, analyzing the time-of-flight and dielectric properties to estimate moisture content.
- **Viewing Results:** Within seconds, the moisture content is displayed on the screen, accompanied by a visual indicator (e.g., color-coded bar or gauge) highlighting whether the beans fall within an ideal moisture range for roasting. For advanced users, the system provides an option to view detailed metrics, such as dielectric constant readings and moisture percentage.
- **Data Management:** Users can choose to save the results to the device's memory or export them via USB for further analysis. This feature is especially valuable for producers who need to log data for quality control or compliance purposes.
- **Maintaining the System:** The software includes prompts for routine calibration checks to ensure long-term accuracy. Additionally, the device provides troubleshooting tips in case of measurement anomalies or user errors.

The interface prioritizes simplicity for beginners while offering advanced features for professionals. By combining straightforward setup, quick readings, and detailed insights, the system empowers users to make informed decisions about their coffee quality with minimal effort.

2.6 Verification plans

We will verify the accuracy of our product by comparing its results to those of the RoastRite™ Coffee Meter, a proven tool for measuring coffee bean moisture content.

The testing process begins with multiple bags of green coffee beans. A bag will be selected at random, and its moisture content measured using the RoastRite™ Coffee Meter. This value will serve as the benchmark for our millimeter-wave radar system. While our initial goal was to achieve results within 20% of the benchmark, we aim to reduce this error margin to within 5%.

We will repeat the process for additional bags, averaging the deviations between our product's measurements and the RoastRite™ results to evaluate overall performance. All testing will follow the provided user instructions without any modifications.

2.7 Risks

Key risks for our project include:

- The radar module may not be as accurate as anticipated.
- Difficulty consistently detecting beans due to their size being comparable to the RF signal wavelength.

Although the extent of these risks is uncertain, we are exploring potential solutions. One idea is to adjust the angle of the transmitted signal to improve measurement accuracy. However, the interaction between the signal and similarly sized coffee beans remains unclear, so testing will begin as soon as possible to address this issue.

A critical challenge is determining how to effectively reflect the signal. While we were provided with an initial test setup, it has proven unreliable and may require redesigning. Resolving this will be a significant step toward refining our testing and code development process.

Another consideration is how to handle the collected data. Older XM125 modules support machine learning, while newer versions do not. Although we've discussed using machine learning, it's unclear whether it would simplify or complicate the process. Further testing and analysis will help determine the best approach.

2.8 Deliverables

Course Deliverables

- Project proposal
- Weekly Progress Reports
- Final report
- ECE Capstone Poster Session poster
- Detailed design documentation, explaining what our design does, how our design works, and why we made the decisions we did
- Bill of materials and pricing
- User's manual
- Version control
- A working prototype
- A manufacturable design

Industry Sponsor Deliverables

- Must:
  - A USB-powered prototype system that demonstrates the ability to use millimeter-wave RADAR to perform non-destructive material detection and classification
  - Software that computes the dielectric constant of a sample from RADAR returns
  - A graphical user interface (on a computer) that can display both RADAR return signals and dielectric constant estimates in real time
- Should:
  - Software that computes the water content of coffee beans from the estimated dielectric constant
  - A graphical user interface (on a computer) that can display RADAR return signals, dielectric constant estimates, and moisture values in real time
  - Software to remove the contribution of user-made sample holders from the RADAR return

Product delivery method to be determined w/ Industry Sponsor

3 Project Management Plan

3.1 Timeline, with milestones

Our project schedule can be found at: COATL-RADAR Project Schedule

3.2 Budget and Resources

The budget is currently loosely defined - specifics will be determined soon. We currently have 2 XM125 radar modules, and 2 more have been ordered. We also are in the process of determining our budget for 3D printing. The industry sponsor will be providing us with the coffee samples needed for testing.

We will conduct most of our experimentation in FAB 60-14, otherwise known as the "Balloon Lab". Additionally, we will be using the EPL as a resource for on-the-fly, as-needed components, as well as 3D printing. We intend to purchase a locker in the EB to store fragile and/or sensitive devices/components.

3.3 Intellectual Property Discussion

The industry sponsor has yielded all IP to the creators. Nothing is currently licensed, but a discussion about patenting will take place after the project is completed.

3.4 Team

Henry Sanders, FA Coordinator

Henry is the group's record keeper, documentation expert, and power engineer. He will ensure all documentation requirements are met, assist with programming, and work on researching and implementing the dielectric constant calculations. He is currently researching power sources for the design.

Skills:

- Power Systems
- Python, C, Assembly
- Technical Communication/Writing

Chris Kane-Pardy, IS Coordinator

Chris is currently working on interfacing with the XM125, specifically researching alternative methods of programming and displaying the reflected waveform. Additionally, he will be in charge of 3D modeling.

Skills:

- Hardware Architecture Design
- Microelectronic Circuit Design
- 3D Modeling

Wallace McKenzie

Wallace is the resident optics engineer and will be looking into the best ways to manipulate the XM125's millimeter wave to suit the needs of the project. Additionally, he will be assisting with programming and managing the project.

Skills:

- Embedded Systems, Microcontrollers, ESP-IDF
- Leadership, project tracking, project management
- Applied Optics

Kamal Smith

Kamal will be tackling the machine learning aspect of this project, if there ends up being one (TBD). He will also be assisting with research, programming, 3D modeling, and project scheduling.

Skills:

- Code Debugging
- Hardware design
- PCB Circuit design

3.5 Development Tools and Process

Project Management Methodology

We will be adhering to a project schedule/timeline as outlined in section 3.1. We have weekly stand-ups on Wednesdays from 7:30pm-8:30pm, and group work sessions on Fridays from 1:00pm-5:00pm. Research and work assignments for the following week will be designated during stand-up.

Collaboration Tools

- Email
- Discord
- Google Drive
- GitHub
- Overleaf (LaTeX)
- Google Calendar
- Zoom

Technical Tools

- STM32CubeProgrammer
- Python (Spyder 6 IDE)
- Fusion 360
- Lucid FlowCharts
- Excel/Google Sheets
- KiCAD (TBD)