Millimeter-wave RADAR to assess the quality of green coffee

Community Partner: COffe And Telesinsing Lab (COATL)

Background and Motivation

Coffee (coffea) is one of the most-traded commodities in the world (at the turn of the millennium coffee was the second most-traded commodity after oil). Grown at low latitudes around the world, coffee represents an important cash crop for millions of people. After coffee “cherries” have been picked, the seed (coffee bean) is fermented, separated from the fruit, and dried. These processing methods reduce the moisture in coffee from ~%50 to <15%.

According to the Specialty Coffee Association, green coffees with moisture levels in the range 10-12% are generally sold at elevated marked prices, slow the rate of degradation during storage, and reduce the risk of microbial fouling. Given the influence of moisture on income, producers and importers carefully track the water content of their beans. For roasters, knowing the moisture content of beans is also critical. Roasting brings our all the flavors and aromas locked inside the coffee. However, the manner in which a particular coffee is roasted (temperature, duration, etc) depends on its water content. Thus, it’s important that specialty roasters are able to measure their moisture content.

Figure 1: Green coffee on drying beds (DailyGrind)

Currently, two main methods exist to measure moisture in green coffee. One method is to bake green beans at 105°C in a convection oven for 24 hours and the weight loss is recorded. While this method is relatively straightforward, it relies on accurate scales (which can be expensive) and is a destructive testing method (some of the beans are lost). Another method is to use a capacitive moisture sensor (Figure 2a). Here, green beans are placed into the space between two electrodes and their dielectric constant is measured. Although this method is quite accurate, capacitive sensors can be prohibitively expensive (especially for producers).

Objective

Based on work with other crops, this project will develop a low-cost coffee moisture sensor based on the commercially-available XM112 60GHz millimeter-wave RADAR module (Figure 2b). Given the strong absorption of water at 60GHz, this module is sensitive to very small amounts of moisture. Indeed, its has recently been used to monitor the withering (drying) of leaves. The XM112 RADAR works by time-of-flight: it transmits a series of pulses and measures the time delay between transmitted and received waves. The amplitude of the return signal depends on the distance to the coffee (*D*), the RADAR cross section (*RCS*), and the reflectivity (γ). This last parameter (reflectivity) is directly affected by the relative permittivity of the material coffee under test (coffee) and can be described by equation:

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

where ϵ_1 and ϵ_2 are the relative permittivities of the materials on either side of the air-coffee boundary. Since the permittivity of the coffee will vary with water content, the reflectivity provides information about moisture in the coffee.

A sketch of a possible RADAR-based moisture sensor is rendered in Figure 2c. This system consists of (1) the XM112 module, (2) a sample holder in which beans (4) may be placed, and (3) a corner reflector. When the sample holder is empty, emitted millimeter wave pulses (5) are returned with high amplitude from the corner reflector. To prevent the sample holder from influencing the measurement, it must be constructed from a material that is “invisible” to 60 GHz. When the sample holder is filled with green coffee beans, the pulses experience attenuation (6) related to the amount of water in the coffee beans. Raw measurements from the XM112 are then processed by computer or microcontroller to extract the sample’s dielectric constant. To validate the sensor’s operation, estimates of coffee moisture will be compared to measurements made with a professional capacitive type sensor.

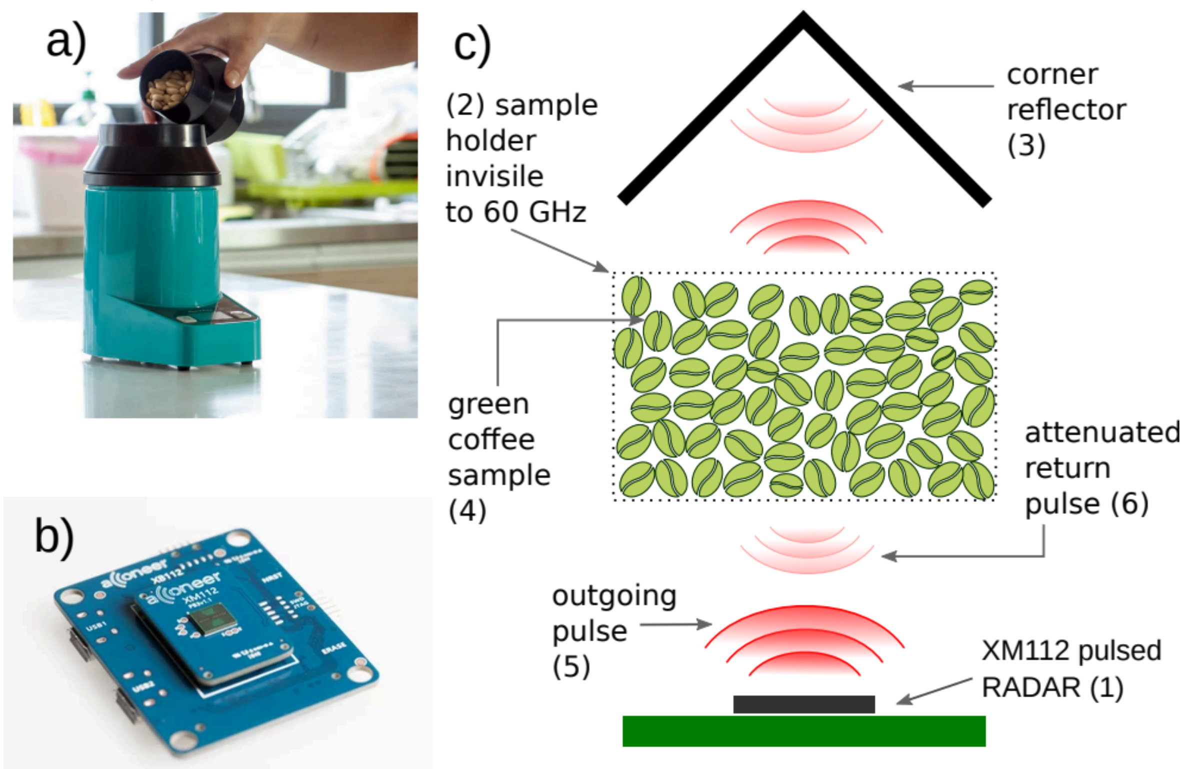

Figure 2: a) Commercial (and expensive) capacitive moisture. b) 60 GHz XM112 pulsed RADAR. c) Conceptual model of material sensing with 60 GHz RADAR for coffee.

Requirements

- Must
  - Be able to extract the dielectric constant 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

Suggested Skills

The student team will need a mix of skills, including programming in C and Python, familiarity with Linux computers, design of RF systems, mechanical CAD design, and 3D printing. Additional valuable skills include familiarity with machine learning algorithms, board layout and fabrication, and basic machining. Being a coffee nerd helps.

Deliverables

Besides the course deliverables, students will deliver:

- 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