3. DESIGN

3.1 PROJECT MANAGEMENT/TRACKING PROCEDURES

3.1.1 BROADER CONTEXT

Describe the broader context in which your design problem is situated. What communities are you designing for? What communities are affected by your design? What societal needs does your project address? List relevant considerations related to your project in each of the following areas: (1) Public Health; (2) Global, cultural, and social; (3) Environmental; (4) Economic → SEE TABLE IN TEMPLATE DOC

Design problem context: There is a considerable need in both the industrial and medical field to identify obstacles hidden behind opaque structures. Failure to do so can and does lead to avoidable damage or inaccurate diagnostic measurements.

Communities: The communities we are designing for include the construction industry, the electrician profession, the craftsman profession, and the health care industry. Each of these industries will be affected by our design because we aim to provide them with a tool that will ensure they are performing safe, well-informed work.

Societal Needs: The problem this project will solve is the need to identify objects that cannot be viewed at the surface level of various types of materials. Identifying such features is necessary to avoid damage to the hidden structures (in the construction industry) or to perform accurate diagnostic testing (in the healthcare industry).

Public Health Impact: In the healthcare context, lacking a diagnostic tool for imaging below the layer of tissue visible to the human eye can lead to missing concerning anomalies below the epidermis layer of the skin. In turn, this can result in avoidable complications and undesirable healthcare outcomes.

Global, Cultural, and Social Impact: Two primary industries are impacted by our product—construction and healthcare. Many professions make up these two broad industries. For construction, this includes construction workers, electricians, plumbers, craftsman, and the like. For healthcare, this includes x-ray technicians, nurses, doctors, and the like. It is likely that widespread adoption of our solution would lead to changes in these professionals' day-to-day activities, but it is unlikely to cause a significant cultural impact unless pricing structures only favor wealthy individuals.

Environmental: Fortunately, our product design does not require regular consumption of environmentally harmful goods. The components used in the product design and manufacture, however, may include plastics and precious metals. We will seek to source environmentally friendly parts, but there will be some waste during the testing and implementation stages.

Economic: This project has significant economic implications for the construction and healthcare industries. Untold damage and countless amounts of money are spent on retroactive repairs of utilities damaged during construction. This tool, taken to its logical implementation and adoption limit, could—for example—help avoid the costly necessity for proactive mapping of structures (because they can always be found later with our tool) as well as retroactive repair of damaged hidden structures.

3.1.2 USER NEEDS

List each of your user groups. For each user group, list a needs statement in the form of:

User group needs (a way to) do something (i.e., a task to accomplish, a practice to implement, a way to be) because some insight or detail about the user group.

Industry #1 – Construction

User Groups: (1) construction workers, (2) electricians, (3) plumbers, (4) craftsmen

- Construction workers need a way to identify hidden building structures because they can damage these structures during construction with heavy machinery if they cannot see them.
- Electricians need a way to identify hidden utilities such as cables because utility cables are easily damaged if a clear understanding of the workspace is unavailable.
- Plumbers need a way to identify pipes hidden behind walls because they must repair and maintain these hidden pipes in a cost-effective manner.
- Craftsmen need a way to identify hidden structures in buildings because they often perform maintenance, remodeling, and repair and can lose money on their work if they cause damage to hidden structures.

Industry #2 – Healthcare

User Groups: (1) radiologists, (2) x-ray technicians, (3) nurses, (4) doctors

- Radiologists and x-ray technicians need a way to render images of tissue anomalies below the epidermis skin layer because their jobs require creation and interpretation of images that display bone, organ, and tissue damage, or abnormal growth below the outer skin layer.
- Doctors and nurses need a way to provide accurate diagnoses of concerning biomedical anomalies via imaging of such anomalies because they are required to properly identify underlying causes of illnesses and devise treatment plans accordingly.

3.1.3 PRIOR WORK/SOLUTIONS

Include relevant background/literature review for the project

– *If similar products exist in the market, describe what has already been done*
– *If you are following previous work, cite that and discuss the **advantages/shortcomings***
– *Note that while you are not expected to "compete" with other existing products / research groups, you should be able to differentiate your project from what is available. Thus, provide a list of pros and cons of your target solution compared to all other related products/systems.*

Detail any similar products or research done on this topic previously. Please cite your sources and include them in your references. All figures must be captioned and referenced in your text.

Similar products:

There are prior solutions, products, and work related to identifying hidden structures in buildings or providing biomedical imagining. To our knowledge, however, very few of these applications use radio frequency (RF) antennas to propagate and then receive signals. The existing market solutions are detailed below:

- **Stud finders**[1] – stud finders frequently use magnets or electricity to detect studs
  - ***Pros*** – this technology is well understood and has existed for a long time; stud finders are cheap
  - ***Cons*** – stud finders do not provide images of the items that are behind a wall; applications are limited application (specifically finding studs in walls)
- **Metal detectors**[2] – metal detectors work by transmitting an electromagnetic field from the search coil into the ground
  - ***Pros*** – long-standing technology that works well for what it does; easy-to-use with little to no learning curve
  - ***Cons*** – only works with metal objects; most do not provide clear 2D rendering of the object below the surface

[1] *Source*: https://www.mrhandyman.com/tips-ideas/handyman-tool-videos/stud-finder/
[2] *Source*: https://www.minelab.com/knowledge-base/getting-started/how-metal-detectors-work

There are also prior solutions, products, and work related to biomedical imaging. To our knowledge, however, none use radio frequency antennas to propagate signals and then receive distorted signals to image the source of the distortion. Pros and cons are omitted below because our system deliverable is less likely to properly function for this purpose by the end of our Senior Design class. However, it is worth noting how similar the functionality of an ultrasound machine is (using sound pulses instead of radio frequency signals). The existing market solutions for biomedical imaging are below:

- **X-ray machines**[3] – "Today's x-ray machines produce a stream of electromagnetic radiation that interacts with an anode in an x-ray tube. The x-rays made by this interaction are then directed toward the part of the body being examined."

- **Ultrasound machines**[4] – "The ultrasound machine transmits high-frequency … sound pulses into your body using a probe. … Some of the sound waves get reflected back to the probe, while some travel on further until they reach another boundary and get reflected. The reflected waves are picked up by the probe and relayed to the machine. The machine calculates the distance from the probe to the tissue or organ (boundaries) using the speed of sound in tissue … and the time of each echo's return... The machine displays the distances and intensities of the echoes on the screen, forming a 2D image."

- **CT scan machines**[5] – "A CT scanner emits a series of narrow beams through the human body as it moves through an arc. This is different from an X-ray machine, which sends just one radiation beam. The CT scan produces [more detail] than an X-ray image."

Related research:

We have conducted significant background research on the cutting-edge of RF antenna array imaging technology. The three primary references we are relying upon are listed below:

A. Haryono, K. Aljaberi, M. Rahman, and M. A. Abou-Khousa, "High Resolution and Polarization Independent Microwave Near-Field Imaging Using Planar Resonator Probes," *IEEE Access*, vol. 8, pp. 191421–191432, Oct. 2020.

M. A. Abou-Khousa and A. Haryono, "Array of Planar Resonator Probes for Rapid Near-Field Microwave Imaging," *IEEE Transactions on Instrumentation and Measurement*, vol. 69, no. 6, pp. 3838–3846, Jun. 2020.

M. Abou-Khousa, K. T. M. Shafi, and X. Xingyu, "High-Resolution UHF Near-Field Imaging Probe," *IEEE Transactions on Instrumentation and Measurement*, vol. 67, no. 10, pp. 2353–2362, Oct. 2018.

[3] *Source*: https://www.wonderopolis.org/wonder/how-does-an-x-ray-work
[4] *Source*: https://www.physics.utoronto.ca/~jharlow/teaching/phy138_0708/lec04/ultrasoundx.htm
[5] *Source*: https://www.medicalnewstoday.com/articles/153201#what-is-a-CT-scan

3.1.4 TECHNICAL COMPLEXITY

Provide evidence that your project is of sufficient technical complexity. Use the following metric or argue for one of your own. Justify your statements (e.g., list the components/subsystems and describe the applicable scientific, mathematical, or engineering principles)

(1) The design consists of multiple components/subsystems that each utilize distinct scientific, mathematical, or engineering principles –AND–

(2) The problem scope contains multiple challenging requirements that match or exceed current solutions or industry standards.

Our design contains multiple components and subsystems that each utilize distinct engineering skills like circuit design, signal processing and propagation, antenna design, and programming. Furthermore, the scope of the problem we seek to solve contains multiple challenging requirements that match or exceed current solutions and industry standards.

A task list for this project—and the engineering principles implicated—are below:

- **Antenna CST Modeling, Design, and Tuning** – CAD modeling, VBA programming, signal transmission and processing
- **RF PCB Design (PLL & Switches)** – complex circuit design, signal reception and processing, circuit board customization, data transfer
- **ADC PCB Design** – programming, data sheet interpretation, data reception and transmission, printed circuit board design
- **Low Level Programming (Data Gathering)** – data reception, microprocessor programming, custom code infrastructure development
- **Data Processing and Display** – user interface design, data processing, data display, programming in Python

The list above makes clear that there are several distinct subsystems in our project. Each subsystem requires unique scientific, mathematic, and engineering principles.

3.2 DESIGN EXPLORATION

3.2.1 DESIGN DECISIONS

List key design decisions (at least three) that you have made or will need to make in relation to your proposed solution. These can include, but are not limited to, materials, subsystems, physical components, sensors/chips/devices, physical layout, features, etc.

We have faced several design dilemmas that have required calculated decisions.

1. **Microprocessor** – We had to carefully consider whether to use a Raspberry Pi, ESP32, or other microprocessor. Ultimately, we chose to use a Raspberry Pi because it has a much broader spectrum of potential functionality.

2. **User Interface Display** – We contemplated as a team whether to use a dedicated external display or design a way to project our user interface on most electronic devices. Ultimately, we decided to write a Python script that would allow us to present our data display on most electronic devices (like smartphones or laptops). This will likely take more work, but it will make our complete system more versatile.

3. **One Fixed Design vs. Two Designs with a Portable Version** – Initially, our client was considering requiring that we build two devices. The first device would be fixed in place like the imaging machines at airport TSA checkpoints. The second device would be handheld. However, after deliberating, we negotiated with the client to drop the second device requirement. This would have required an enormous secondary effort and recalibration of all other project subsystems. Nevertheless, the second version would have been interesting and useful in many distinct ways.

3.2.2 IDEATION

For one design decision, describe how you ideated or identified potential options (e.g., lotus blossom technique). List at least five options that you considered.

Our microprocessor presents a strong example of many different potential options requiring one final decision. We engaged in structured ideation to reach a single conclusion.

The options we considered were as follows:

- **Raspberry Pi**[6] – "The Raspberry Pi is a tiny and affordable computer that you can use to learn programming through fun, practical projects."
- **Teensy 4.0**[7] – "The Teensy is a complete USB-based microcontroller development system, in a very small footprint, capable of implementing many types of projects."
- **ESP32**[8] – "ESP32 is a feature-rich MCU with integrated Wi-Fi and Bluetooth connectivity for a wide-range of applications."
- **ESP8266**[9] – "ESP8266 is a cost-effective and highly integrated Wi-Fi MCU for IoT applications."
- **Teensy 3.9**[10] – "The Teensy is a complete USB-based microcontroller development system, in a very small footprint, capable of implementing many types of projects."
- **Arduino Mega**[11] – "The Arduino MEGA 2560 is designed for projects that require more I/O lines, more sketch memory and more RAM."

[6] *Source*: https://www.raspberrypi.org/
[7] *Source*: https://www.pjrc.com/teensy/
[8] *Source*: https://www.espressif.com/en/products/socs/esp32
[9] *Source*: https://www.espressif.com/en/products/socs/esp8266
[10] *Source*: https://www.pjrc.com/teensy/
[11] *Source*: https://www.arduino.cc/en/Guide/ArduinoMega2560/

3.2.3 DECISION-MAKING AND TRADE-OFF

Demonstrate the process you used to identify the pros and cons or trade-offs between each of your ideated options. You may wish you include a weighted decision matrix or other relevant tool. Describe the option you chose and why you chose it.

Ultimately, we settled on the Raspberry Pi because it was the strongest combination of features needed for our project. The factors we considered are below:

- **Simplicity –** It is generally understood that the Raspberry Pi is the easiest to use of all the microprocessor options. It is also the easiest to program for user interface data display.
- **Self-Contained –** With the Raspberry Pi, we do not have to create a breakout board for it unlike other MCUs.
- **Existing Libraries –** Many libraries already exist for Raspberry Pi so it will require less low-level programming.
- **GPIO Pins** – We wanted to maximize this factor, but the Raspberry Pi is actually not the industry leader in this regard.
- **Quad Core Capability** – Can run multiple processes in parallel, which is not just ideal, but crucial to the data gathering and post processing tasks of the project.

Table 1 – Microprocessor Decision Matrix

Option	Simplicity	Self-Contained?	Existing Libraries?	GPIO Pins?	Quad Core Capability
Raspberry Pi	Very Simple	Yes	Yes	Enough	Yes
Teensy 4.0	Moderate	Not as well	Limited	Many	None
ESP32	Challenging	Not as well	Limited	Some	None
ESP8266	Challenging	Not as well	Limited	Some	None
Teensy 3.9	Moderate	Not as well	Limited	Some	None
Arduino Mega	Simple	Yes	Yes, but less	Many	None

A variation of a decision matrix is provided above in Table 1. It pictographically depicts why the Raspberry Pi was our strongest choice for microprocessor.

3.3 PROPOSED DESIGN

Discuss what you have done so far – what have you tried/implemented/tested?

3.3.1 DESIGN VISUAL AND DESCRIPTION

Include a visual depiction of your current design. Different visual types may be relevant to different types of projects. You may include: a block diagram of individual components or subsystems and their interconnections, a circuit diagram, a sketch of physical components and their operation, etc.

Describe your current design, referencing the visual. This design description should be in sufficient detail that another team of engineers can look through it and implement it.

Our project is a series of subsystems that comprise a complicated circuit. We have modeled this circuit, and our model layout is displayed in **Figure 1 below**.

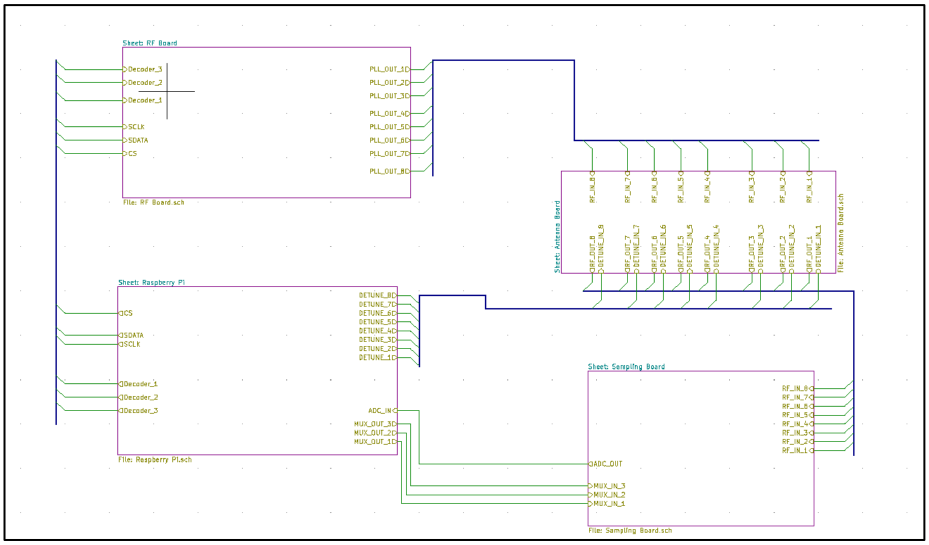

Figure 1 - Full System Circuit

The upper right quadrant of Figure 1 represents our RF antenna array. It includes eight I/O ports for each of the eight antennas.

The lower right quadrant of Figure 1 represents our ADC PCB. This will take signals from the RF antenna array and pass them to the microprocessor for processing and display.

The lower left quadrant of Figure 1 represents our microprocessor. It will send user-input commands to the RF PCB and receive data from the ADC PCB.

The upper right quadrant of Figure 1 represents the RF PCB. It will receive and transmit power, receive signals from the antenna array, send commands to the antenna array, and receive user-input commands from the microprocessor.

Figure 2 below displays the simulation and modeling step in the broader process of designing and ordering the antennas that will comprise our antenna array.

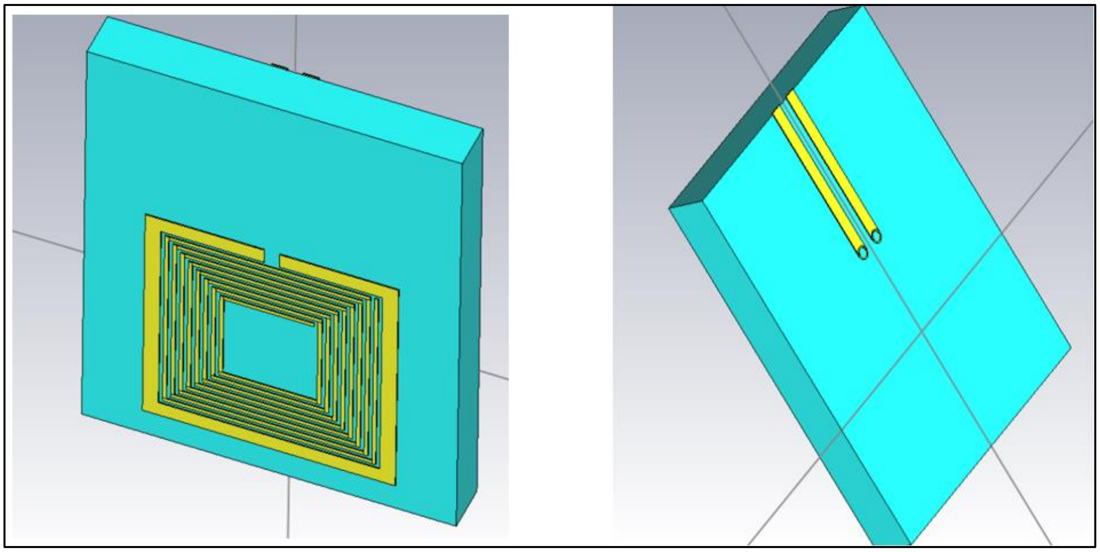

Figure 2 - Antenna Model and Simulation

The image at left in Figure 2 is the antenna side that will propagate signals into the medium we seek to measure. The image at right in Figure 2 is the "feed" side which will be connected to the RF PCB.

Figure 3 below displays an example of the CST simulations we are using to design the functional aspects of our antennas. We must place eight such simulated antennas in an array to predict and account for crosstalk and interference.

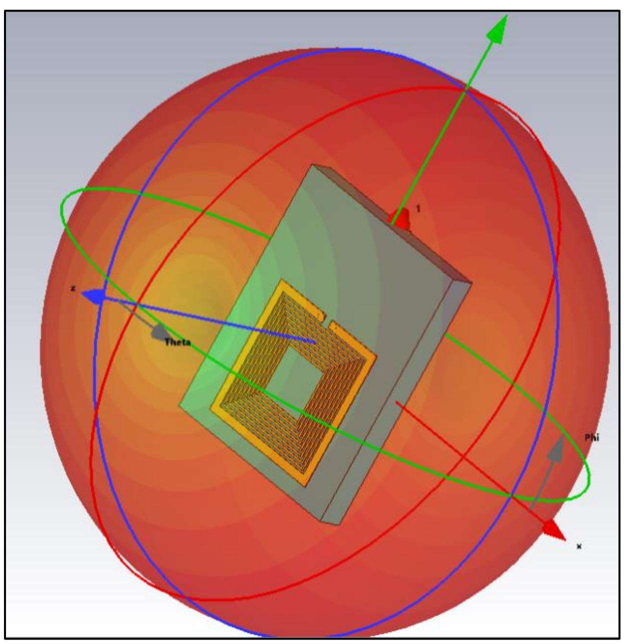

Figure 3 - Antenna Model CST Simulation

Figure 4 below displays the complete circuit diagram for our RF PCB.

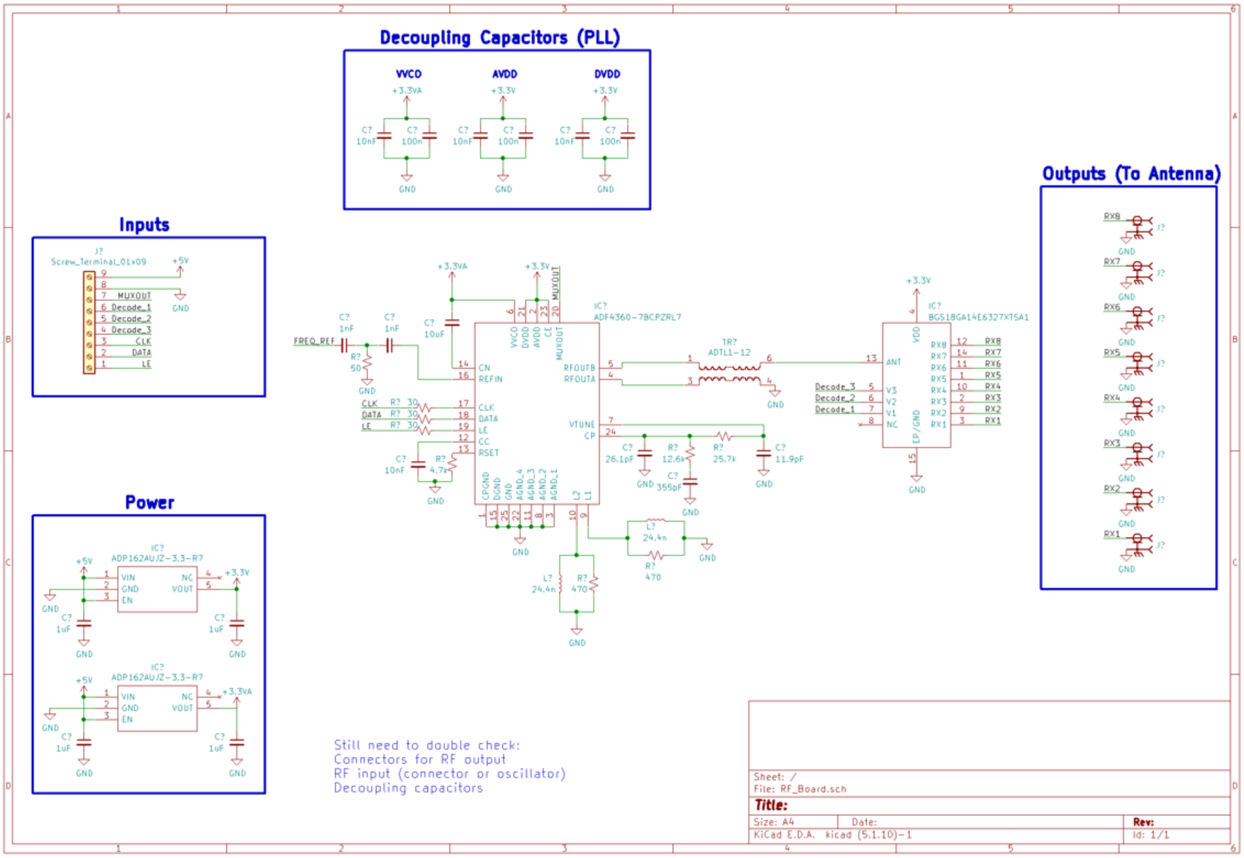

Figure 4 - RF PCB Schematic

The seemingly complicated circuit in Figure 4 severs several distinct—and conceptually elementary—purposes. The RF PCB's primary purpose is to control and measure the signals that the antennas propagate and receive. It will also maintain a baseline signal that our system will use as a constant to measure discontinuities in the mediums we are measuring.

3.3.2 FUNCTIONALITY

Describe how your design is intended to operate in its user and/or real-world context. This description can be supplemented by a visual, such as a timeline, storyboard, or sketch.

How well does the current design satisfy functional and non-functional requirements?

Our final design—and our completed system—will be usable and function in two ways.

The first functional use concept will take the form of a stationary device that objects are fed through or under. This design concept will be similar to the TSA scanners at airport checkpoints. Critically, TSA scanners at airports use radiation from x-rays to create images of luggage content. Of course, our system will use RF antenna propagation and measurement instead. Our system is likely also to be much smaller than the standard TSA checkpoint x-ray scanner. Figure 5 below displays the "feed through" functional concept we will implement as one possible use method for our complete system.

Figure 5 - TSA Checkpoint Machine Functional Use Example[12]

[12] *Source*: https://www.tsa.gov/news/press/releases/2020/08/27/tsa-checkpoint-norfolk-international-airport-gets-new-state-art-3-d

The second functional use concept will take the form of a handheld device that can be moved over the surface that our system is measuring through. This functional form of use will be like a stud finder. Figure 6 below displays the handheld stud finder use method that exemplifies the way a user will be able to use our complete system.

Figure 6 - Handheld Stud Finder Use Concept Example[13]

Functional Limitations and Non-Idealities:

Our complete project system will be mounted in a 3D printed thermoplastic bracket. It will necessarily be more unwieldy than a small and compact stud finder. Furthermore, it will be a fraction of the size of a TSA scanner, so it will not be able to scan through objects as large as a suitcase at one time like a TSA scanner. This is consequence of the necessity to create prototypes and a byproduct of our temporal limitations. Future iterations of the project would be smaller, more space efficient, and easier to use in a handheld capacity.

[13] *Source*: https://www.bobvila.com/articles/how-to-use-a-stud-finder/

3.3.3 AREAS OF CONCERN AND DEVELOPMENT

Based on your current design, what are your primary concerns for delivering a product/system that addresses requirements and meets user and client needs?

What are your immediate plans for developing the solution to address those concerns? What questions do you have for clients, TAs, and faculty advisers?

Table 2 below displays our primary design concerns, our projected solutions for such concerns, and questions we have not yet solidified answers for.

Table 2 – Primary Design Concerns, Projected Solutions, and Lingering Questions

Design Concerns	Projected Solutions	Lingering Questions
Usability – design dimension uncertainty	We will minimize the size of the device while optimizing power and speed.	Final design dimensions? When will we know?
Using Python (a high level language) to handle high frequency ADC analog signals (a very low level process)	If we find that using python will slow down the functionality of our project, we will likely use C instead of python to handle the data gathering and post processing tasks.	When to use C vs. Python?
Over complexity – # of subsystems	Simplify processes or reduce functionality/speed to ensure min. viable functionality	How to find balance of consistent capability vs adding new features/functionality?
User interface interpretability	Conduct usability studies with intended end users for feedback on data visualization intuitiveness	What are the best usability studies to obtain effective feedback from end users?

NOTE: The following sections will be included in your final design document but do not need to be completed for the current assignment. They are included for your reference. If you have ideas for these sections, they can also be discussed with your TA and/or faculty adviser.

3.4 TECHNOLOGY CONSIDERATIONS

3.5 DESIGN ANALYSIS

3.6 DESIGN PLAN