Dual-Antenna RADAR System

6.2300 Class Project: Final Report
TeamID: 2DLocalization

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***Abstract*—We propose a dual-antenna setup that, using time-domain reflectometry (TDR), detects the distance to objects at various angles, allowing us to determine their positions in a small-scale RADAR system. Two identical horn antennas (one for transmitting and one for receiving) are designed and fabricated from aluminum cans to operate at an FCC-approved frequency of 3.246 GHz.**

I. Introduction & Motivations

The need to detect the position of an object arises in many applications, such as defense (for detecting the position of vehicles on the battlefield) or autonomous cars (for detecting the position of cars, pedestrians, or other road hazards). In both these application areas, the ability to accurately detect the position of an object is critical for both safety and to make well-informed decisions. RADAR is one method of performing distance measurement using electromagnetic waves, and an example application for detecting planes is illustrated in Fig 1.

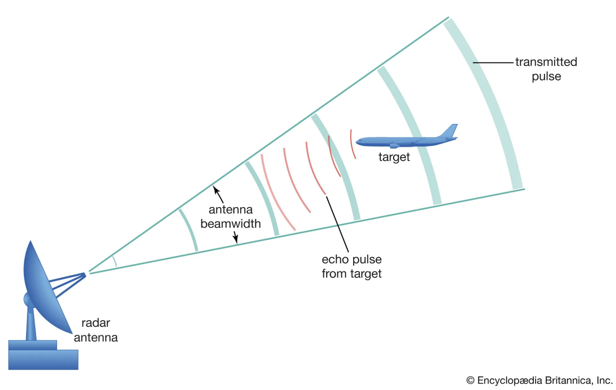

Fig. 1: Radar antennas can be used to detect the distance to a target such as a plane. [1]

One application area for RF localization explored by Adib et al. is the detection of people in their homes using a transceiver-free system based on frequency modulated continuous wave (FMCW) with four directional log-periodic antennas (one for transmitting and three for receiving) [2]. In a different paper, Moses et al. developed a small, lightweight RADAR system for UAVs to identify other UAV-sized targets. The RADAR is implemented via a horn antenna [3].

Position detection is also utilized in autonomous vehicles. A device known as LiDAR records the time interval a laser it produces takes to reflect back to it, allowing for accurate distance calculations. Research into combining lasers with computer vision is intended to offer a cost-effective alternative to current position detection systems [4]. Additionally, Satoh et al. has estimated the position of wireless access points by developing a model that takes in the signal strength measured by a highly directional antenna, the antenna's angle and the user's positional data [5].

Our system implements RADAR based on the principles of time-domain reflectometry. Two identical horn antennas are fabricated from the highly accessible aluminum cans and connected to the ports of a NanoVNA to transmit and receive a frequency sweep as described in section II. Our final system had basic functionality but poor precision, as discussed in sections IV and V.

II. Approach

This project is inspired by the portion of the time domain reflectometry lab where reflected pulses were used to infer the length of a cable. We are expanding the idea of using these reflected pulses to infer the distance to objects within a grid to implement a position detection system.

The system consists of two directional horn antennas (one for transmitting and one for receiving). The reflected pulse is measured as a time delay corresponding to traveling twice the distance between the antenna setup and the object. The equation (1) below is used to calculate the distance:

$$d = \nu_{\text{prop}} \cdot \frac{t_{\text{delay}}}{2} \tag{1}$$

The horn antennas are designed for 3.246 GHz and fabricated with aluminum cans. Each consists of a cylindrical waveguide attached to a conical flare with diameter determined by equation (2) below [6], where λ represents the wavelength of an operating frequency and L is the length of the flared portion

$$\text{diameter} = \sqrt{3\lambda L} \tag{2}$$

For the cylindrical waveguide, the feed length is approximately $\lambda/4$ (incrementally trimmed based on empirical measurements) and the dimensions of the cylindrical cavity were determined using the tool from the metal cavity lab to have a resonant mode at the operating frequency of 3.246 GHz.

Since we want to send a directed beam, we optimize the design of the antenna for high directionality. The conical horn design was simulated and optimized in Ansys HFSS with the setup and satisfactory radiation pattern shown in Fig 2. The two highly directional horn antennas will interface with the course-provided NanoVNA to transmit and receive signals, as illustrated in Fig 3.

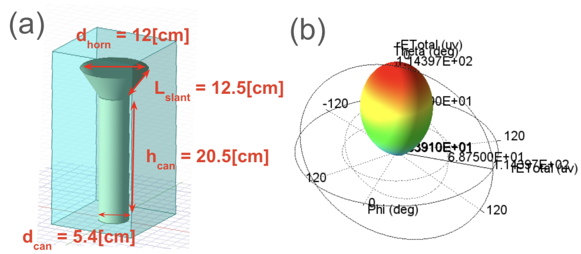

Fig. 2: (a) Ansys HFSS setup with resulting dimensions of horn antenna.
(b) Simulated horn antenna radiation pattern.

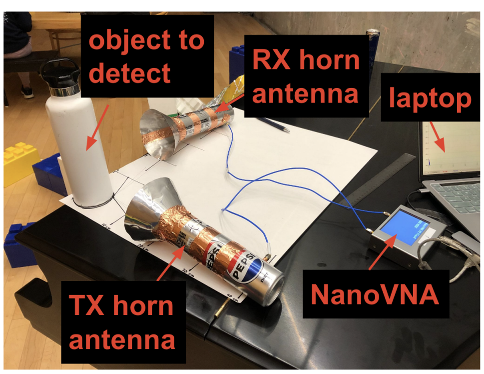

Fig. 3: Setup for detection of an object (water bottle) with two horn antennas.

III. Legality, Safety and Ethics

In accordance with the Federal Communications Commission's guidelines on low-power, non-licensed transmitters [12], we will build our transmitters for personal use as inventors. We have no intentions to market our product and therefore do not need FCC equipment authorization for our endeavors. In compliance with these regulations, we will construct and operate no more than five of our transmitter designs and refrain from causing destructive interference with licensed radio communications. Furthermore, we plan to operate at a frequency of around 3.246 GHz, which is in compliance with government-restricted ranges. In addition, we will ensure that our emissions do not exceed 500 µV/m at 3 meters from our setup using an average peak detector. This will be measured by hooking up our antennas to the TinySA and using its power measurement settings to ensure this restriction is met. In addition, in accordance with the International Traffic in Arms Regulations (ITAR), we will avoid sending our findings on our RADAR system to external national threats or malicious individuals. In general, most of the ITAR restrictions are already accounted for by following the FCC's hobbyist guidelines. Safety concerns may arise with operating our antenna, such as prolonged exposure to high-frequency waves. To circumvent this concern, we will mitigate our exposure to our antenna by turning it off when not in use and spending minimal time in its radiation area when taking measurements and experimenting. Proper engineering ethics and procedures will be followed in the production of this system.

One set of stakeholders directly affected by RADAR technologies are military entities, whose constituents could face severe harm or loss of life due to the information RADAR systems may provide to enemy groups [7]. The application of such systems to 3D motion detection can raise privacy concerns [8], civilians an be directly affected by invasion of privacy from governments or private entities. An example is with Google incorporating RF sensing into smart home devices [9].

Indirectly affected are developers of autonomous vehicles, as our RADAR system could interfere with any electromagnetic sensors present in their vehicles [10]. Additionally, wind energy producers are negatively and indirectly affected. RADAR waves could be reflected off turbines due to their height and size, which interferes with weather forecasting and aviation agencies [11]. This limits this section of the renewable energy market.

IV. Results

Various characteristics of the fabricated horn antennas are measured and displayed in Fig. 4, 5, 6, 7. The significance of the results is discussed in section V.

V. Discussion

Figure 4 shows that both horn antennas are tuned to 3.246 GHz, as demonstrated by the dip in s11. Figure 2 shows that our horn antennas have high directionality, as demonstrated by the singular radiation lobe. This high directionality ensures that only objects directly ahead of the antenna are detected, reducing erroneous measurements.

Figure 5 demonstrates a dramatic increase in received power at 3.246GHz when an object is in front of the horn antennas versus when an object is absent. This demonstrates that our system can, at minimum, recognize when an object is in its path.

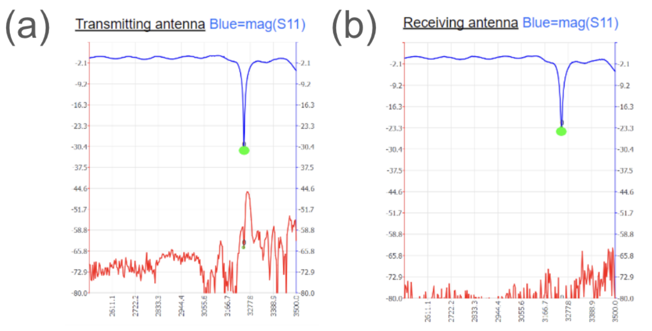

Fig. 4: Magnitude of S11 vs Frequency. The marker is at 3.246 GHz

The right plot of Figure 6 showcases the time domain data from the VNA when an object is successfully detected. The peak in s21 (at -60dB) can be used to calculate the position of the reflective object. In contrast, the left plot of 6 showcases an unsuccessful detection. The peak in s21 (at -75dB) is too small to be distinguished from noise. This was because the reflective object was too far away – the maximum range at which objects could successfully be detected was 1 m.

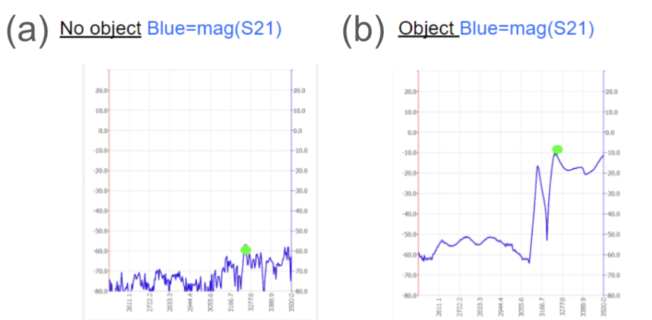

Fig. 5: Received Antenna Power when object absent and present.

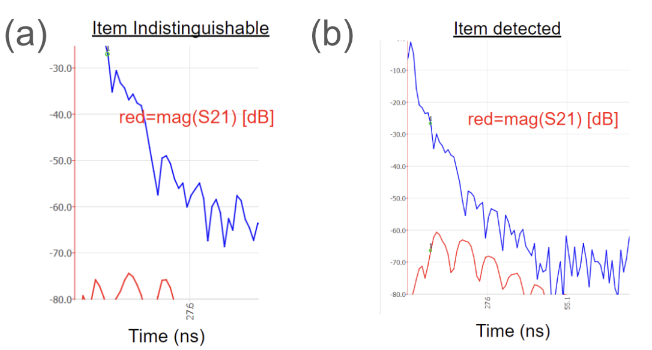

Fig. 6: Time domain data for successful and unsuccessful detections

Based on Figure 7, we determined that our system is currently working rather poorly. While the time delay moves linearly increases as expected, its slope is off by a factor of roughly 3. A potential reason for this discrepancy is the resolution of the nanoVNA's time domain. For our VNA measurements, the bandwidth was 1 GHz to 4 GHz with a 1 MHz step (3,000 points). This means our resolution in the time domain was 0.33 ns, which corresponds to a distance of 10 cm (1/10 of our max measurement distance) for propagation at the speed of light. This means small changes in the location of the peak in the time domain could correspond to large changes in the calculated position.

Another factor to consider is the power output of the nanoVNA. Currently, the nanoVNA outputs power in the range of -10dB to -15dB. With a stronger power output, peaks could be detected from farther away, increasing the acceptable measurement range.

Regarding the point on resolution, increasing the number of points the VNA samples would increase resolution in the time domain, alleviating the difference discrepancy in measured and predicted slope. Alternatively, decreasing the frequency range of the VNA would also allow for finer distance measurements. The latter approach would also make it more difficult to distinguish nearby peaks in the time domain, but since only a single reflection (and therefore, a single peak) is expected in this system this would not be an issue.

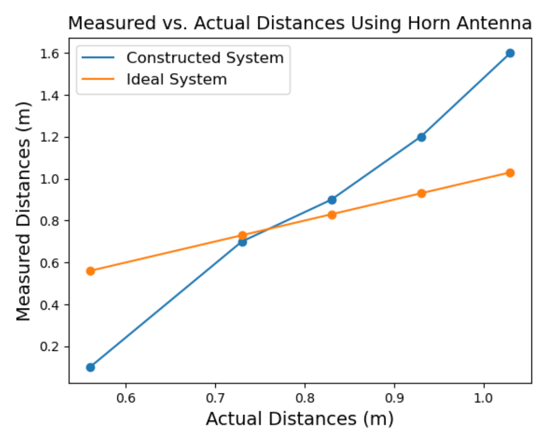

Fig. 7: Actual (orange) vs measured (blue) distance of object using horn antennas.

Regarding the point on power, a future team could use a VNA with higher output power or add an amplifier to the output of a VNA.

VI. Conclusion

In conclusion, we have constructed a system that successfully depicts a linear increase in predicted distance as we increase the actual distance between our antennas and the object; however, it is not precise as the slope of 3.076 is roughly triple the expected slope of 1 between the experimental and actual data.

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