Localization of a Metal Cylinder via Power Transmission Analysis in the 2-3 GHz Band

6.013 Class Project: Detailed Final Report
TeamID: Radiolocator

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***Abstract*—Radiolocation is the process of finding the location of an object through the use of radio waves. This can be accomplished by using data analysis to study the varying degrees of transmitted power within a set of antenna pairs as a result of changing an object's location. In this work, we aim to pinpoint the location of a metal cylinder on a circular field with a .48 meter diameter by analyzing the transmission obtained from three antennas pairs operating within the 2-3 GHz operational frequency band. The applications of radiolocation include wide-range surveillance with resolution on the meter scale, which could benefit national security by enabling the ability to seek out and detect resources in an adversarial country without needing to risk placing assets on the ground.**

I. Introduction & Motivations

Our group first became interested in the radiolocation of large metal objects after watching a piece by 60 Minutes Australia called *Finding MH370* that proposed a method of tracking the lost Boeing 777 via recorded disturbances in amateur radio transmissions [1]. Due to the legal complications associated with tracking planes as well as the extra difficulty provided by Boston's busy airspace, we instead decided to explore other examples of radiolocation. Radiolocation is used in a wide variety of industries in applications such as vehicle tracking, mining, and even avalanche search and rescue which uses the proprietary RECCO reflector system.

In this work, we aim to localize a metal cylinder on a 2D polar grid using three equally spaced antenna pairs along the circumference of the grid. Radiolocation via reflection (TDR analysis), is quite sensitive to many factors such as signal frequency, antenna type, reflector type, and general orientation. Reflection signals are known to be noisy and difficult [2]. Standard TDR analysis is, however, effective in finding a short within a cable, because the vast majority of the reflected signals return to the transmitter. Since our can is instead in free space, the reflections will scatter in different directions, making TDR analysis unfit for this experiment. Because of these complications, we choose to analyze data on power transmission readings between the three antenna pairs.

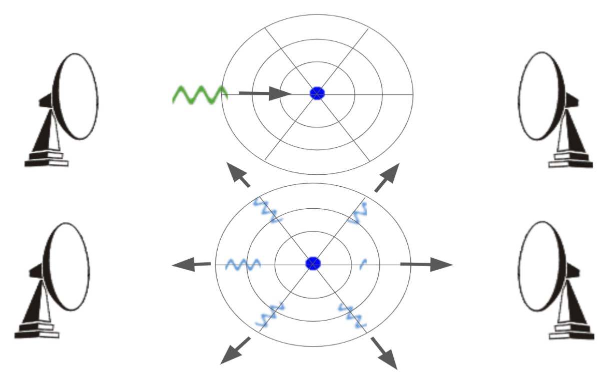

Fig. 1. Schematic of radiolocation principles for applications in surveillance of the dark blue object.

Although using power transmission instead of reflection will give us more total signal to analyze, and thus a diminished effect of thermal noise, our system will still be extremely sensitive to movement up to 10 feet away from the grid. Due to this, it is still fruitful to analyze how TDR systems have ensured a clean return signal so that we can attempt to use ensure a clean transmitted signal. Researching long-range radar surveillance, Hill Galloway found improved detection using ultra high-frequency signals with multi-element arrays [3]. Although we don't need the same range or fidelity, we can learn from their design choices. Olofsson et. al. show another example of researchers solving this problem when analyzing signal reflections from a RECCO patch for avalanche victims. By using a harmonic radar setup and looking for reflections at twice the transmitted frequency, they are able to get consistent signal reflection with accurate distance correlation even in the presence of media obstructions like snow or a human body [4].

Once we have clean transmission signals from each of our antennas, we must move on to the next subproblem: getting an accurate location estimate using these three transmission signals. This subproblem has been researched extensively using reflections, especially in the cell phone industry. Ryden et al. proposed a method to find the time of arrival of return signals by adjusting the signal threshold iteratively instead of setting a fixed signal threshold which may either miss the correct return signal or pick up extra false signals [5]. For our case of using transmission signals, we will take power transmission data from our three antenna pairs with the metal can at a large range of different locations and use the data as a training set for an AI program. The computational aid will then take in the three transmission values corresponding to an unknown location and return it's best three guesses at the can's location based off of the training data set.

II. Approach (aka Materials & Methods)

Quarter wave dipole antennas operating at frequencies of approximately 2.128, 2.424, and 2.285 GHz were used for each pair of antennas. Multiple factors influenced the decision to operate an antenna pair at each of these frequencies. The general range of operating frequencies is ideally above 2 GHz to limit the operating wavelengths with respect to the diameter of the cylinder and the diameter of the plane of localization. The upper bound of this range was set by the operational limitations of the nanoVNAs used to measure the transmitted and received power of each pair of antennas. The particular values of the operating frequencies were chosen to optimize each pair's bandwidth subject to the limitations of our manufacturing processes. Antennas were fabricated and characterized for a wide variety of frequencies in the 2-3 GHz range. The frequencies used were chosen from the set of fabricated antennas to based off of their characteristics. Additionally, the operating frequencies were chosen subject to the limitation that the minimal difference in operating frequencies be greater than .2 GHz in order to limit the effect of any single transmitting antenna on the two receiving antennas it was not intentionally paired to. This enabled simultaneous operation of each independent pair of antennas.

The transmitting antennas were arranged around a circle of radius .24 meters at intervals of 120 degrees. Each corresponding receiving antenna was placed at an equal radius on the opposite side of the circle. S11 and S21 measurements were taken with the cylinder located at 48 points within the circular plane. Measurements were conducted for all three pairs of antennas at 30 degree intervals for radii of .06, .12, .14, and .18 meters. The measurements demonstrated an extreme degree of time variance which was minimized by limiting movement in the vicinity of the experimental setup and extending wires from the experimental setup to the locations where individuals were reading measurements.

The process of using these measurements taken at known positions to locate the cylinder on the plane when its position is not known posed a mathematical challenge. Ideally, a set of six continuous 2-dimensional functions over the surface of the plane would be devised to fit the data of the empiric measurements and would establish predictive contours between known points. This approach would enable a cylinder to be located by comparing measurements associated with an unknown point with the functions formed by the data associated with the set of known point measurements for each operating frequency and measurement type. This approach was not implemented due to the mathematical complexity it involved and the nature of the project we were tasked with completing.

The implemented method is a discrete approximation of the previously described method. In our system, the measurements taken are summed and compared to the sum of measurements associated with every known point. Each known position can then be assigned a probability of being correct based off of the deviation of the new measurements from the measurements of the known point. This method allows for the predicted point to be a weighed average of two or more known points, although in practice the implementation of a deviation-weighted predictive model was restricted to cases where the most likely points were already within a specified distance of each other. Although the measurements taken at known points do demonstrate some trends, the summation of these measurements can result in new measurements demonstrating extremely little deviation from points that are very removed from the actual location of the cylinder. Notably, an alternative model which relied on taking the weighted average of the most likely points determined by the deviation of new measurements from known point measurements for each antenna pair independently was attempted, but was found to demonstrate a significantly higher average error. This is presumed to be because the summing of the measurements for a single point offers a level of noise resistance which was not present in the alternative model. Additionally, the trends demonstrated my the measurements result in some subsets of points for each measurement being somewhat non-unique relative to other points in that subset.

III. Legality, Safety and Ethics

- Legaility

Our team of MIT students is eligible to perform this test of radiolocation techniques due to the protection provided by the Code of Federal Regulations (CFR) Title 47 §90.103. This subpart permits a person engaged in educational or scientific activity to be eligible for authorization to operate a station of radiolocation devices to determine position for purposes other than navigation [9]. This subpart also extends this eligible authorization to a person engaged in industrial or commercial activities. Therefore, if the findings of this small-scale scientific project prove to be applicable in the context of industry and the project is extended to a larger scale, the intent of the project will remain within legal boundaries.

CFR Title 47 §90.103 also places restrictions on certain frequency bands that stations performing radiolocation are allowed to operate within. In the scope of our project, each of NanoVNAs will operate within the range of 2-3GHz and our copper antennas will act as small-scale stations which transmit this frequency signal. Within the band of 2-3GHz, 2450-2500MHz is allocated only to radiolocation purposes on a secondary basis behind mobile or fixed radiocommunication services, thus radiolocation efforts must accept any harmful interference from industrial, scientific, or medicinal equipment operating within this frequency band [9]. Additionally, in the 2483.5-2500MHz band, no applications for new or modification of existing stations to increase the number of transmitters will be accepted [9]. For these reasons, we will avoid operating within the narrow 2450-2500MHz frequency band. This will allow us more confidence in our results due to less undesirable interference. Additionally, it will allow us to maintain the possibility of eventually creating a larger-scale station operating on the same principles without encroaching on legal framework.

- Safety

Safety concerns for the experimental locating of the metal cylinder, using time-domain reflectometry, should be minimal given that we operate within the frequency band of 2-3GHz. The associated wavelengths are not harmful should they be reflected off of the cylinder and intercepted by a person. Therefore, the primary safety hazards associated with this experiment are the fabrication of the copper wire antennas and PCB board micro-strips to which they are attached. The soldering of the antennas to the end of the microstrips will have to be executed carefully because copper is an excellent conductor and should not be directly touched during the soldering. To minimize risk of burning the solderer, we will use a pair of tweezers to hold the copper antenna while attaching it to the PCB board microstrip. We will also minimize the possibility of injury during the fine-tuning of the 50Ohm PCB microstrip by cutting away from ourselves and others with the X-Acto Precision Knife. Moreover, we will adhere to all MIT EECS safety guidelines over the duration of our experimentation.

- Ethics

Two stakeholders that may be affected negatively by the advancement of radiolocation technologies are personal privacy and casualties during war, as tracking valuable targets becomes easier and more accurate than previously possible. Current research in radiolocation techniques to create ultra-high resolution radar-systems aims to achieve the ability to locate and model targets down to approximately 5mm in resolution when operated at 300GHz over short distances [10]. When operated over long distances, for example a satellite to earth, current research aims to achieve resolution on the scale of a meter [10]. Both of these are larger-scale applications of the principles that we are using to pinpoint the coordinates of the metal cylinder. The long distance application of radiolocation techniques lend themselves to surveillance, which can be an unethical breach of privacy if the surveillance is captured in a place where there is a reasonable expectation of privacy, including private residences [11]. This implies that although radiolocation may soon be able to model the contents of a private residence, it is potentially both illegal and unethical to pursue such endeavors. From the scope of war, an increase in resolution of a valuable target will make it easier to locate and strike accurately. Since the Defense Advanced Research Projects Agency (DARPA) has an annual budget of $3.5B, the agency will likely pursue this line of research to protect American technological status and must use the resulting research in accordance with the laws of armed conflict.

IV. Results

Figures 2 and 3 are shown for a single pair of antennas.

The average error of the implemented predictive model is a measurement of distance between the cylinder's predicted location and actual location averaged over multiple tests. It can be measured in two ways. The first method is a characterization of the average error of the predictive model using known points. The algorithm can be used to iteratively predict locations based off of the measurements of a known point while that point is excluded from the set of known points. This process yielded an average error of .103 meters and figure 4 shows the distribution of various degreees of error over the plane. The second method is an average of the best of three predictions for the location of the cylinder resulting from data gathered at randomly selected unknown points, which yielded an average error of .053 meters when tested on five points.

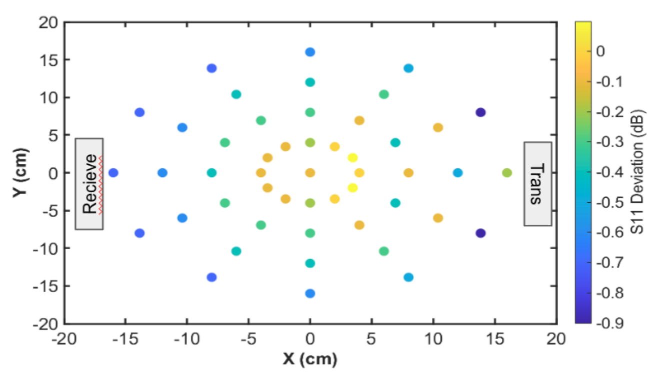

Fig. 2. Heat map of power reflection training set values (S11) as a function of polar location.

V. Discussion

We first analyzed our can transmission model with one antenna pair in the hopes of finding data that fit an intuitive analytical model. However the data fluctuated significantly so we were forced to rely on empirical methods such as fitting, grouping and interpolating to characterize the system. Thus we conducted experiments to find the S21 and S11 deviations due to the introduction of the can present along

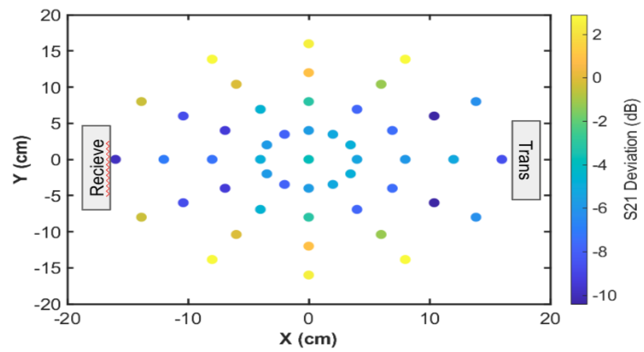

Fig. 3. Heat map of power transmission training set values (S21) as a function of polar location.

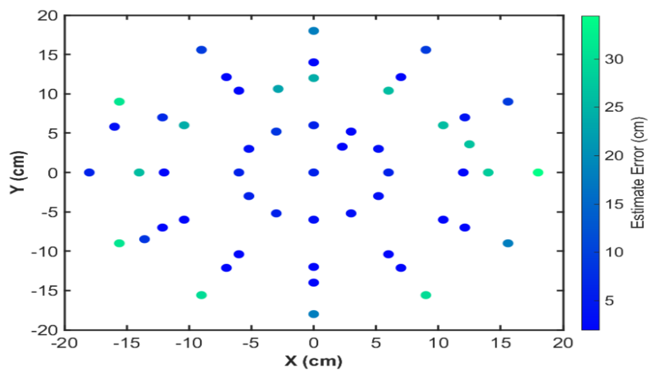

Fig. 4. Heat map of absolute deviation of measured distance from actual distance [cm] for a three antenna set up as a function of polar location.

48 locations in the plane. As shown in Figure 2 we can qualitatively see a clear correlation between the distance in X from the receiver and the deviation in S11. This makes sense intuitively as the locations where the can is closer to the transmitter will see more reflection. In Figure 3, we notice a similar correlation between Y distance and S21 which displays how cans closer to the lines between the two antennas will disturb transmission more. These plots indicate that there are correlations between can location and S21 and S11. If we can quantify these correlations properly then we should be able to predict can locations from S21 and S11 values. We will need multiple antennas, however. Despite the variation of most points on the S11 and S21 plots, the symmetry along both axes will prevent us from predicting unique points that fit both S11 and S21, instead we may see multiple similar points mirrored across the X axis.

We first attempted to characterize the empirical data from the three antenna pair setup with regression tools from MATLAB's Regression Learner toolkit. However due to inconsistency in the data measurements, we could not create clean fits representative of the data. Additionally we tried an approach of using neural net fitting to predict the data outcomes, using Bayesian Regularization. However due to the small size of our dataset, the weights did not increase quickly enough to provide accurate predictions. All of the predictions skewed towards the origin and had mean squared error consistently in the realm of $50(cm^2)$. We also tried different K-Nearest Neighbor approaches to classify test points to their nearest training point. We found some success with this model despite overfitting the data, but determined that a more personalized data processing method was necessary.

The first method for measurement of average error is not reflective of the accuracy of the predictive model when actually implemented because the exclusion of a known point from the data set creates a gap in the distribution of known points twice the size of the largest gap in the model's data when normally implemented. However, the ability to use a large quantity of existing measurements makes this average error estimation method a reliable way to characterize the error of the process when refining or comparing systems and setups. The second method of measuring the average error of the predictive model is more reflective of the average error that could be achieved with superior noise management.

The fact that the best of the three most likely predictions can achieve an average error as low as approximately the radius of the cylinder indicates that there is merit in the principles of the setup. However, it also indicates that an additional process for eliminating noise in measurements may be needed to establish a single prediction as being significantly more likely to be correct than the two next most likely predictions which are being used in the second average error calculation. Additionally, even with some degree of interpolation, the use of a discrete dataset in place of a continuous two dimensional function to characterize the expected measurements at all points in the plane creates a lower bound on the possible error that can be achieved. The visible patterns in figures 2 and 3 indicate that a two dimensional function for both the S11 and S21 measurements of each antenna pair could be implemented with continuous countours to include the finite set of datapoints used to contrive the functions.

VI. Conclusions

A .05 meter average minimum error of three predictions of the location of a .08 meter diameter cylinder in a .48 diameter circular plane demonstrates that the premise of the project is sound, but that additional attention would need to be given to the implementation to achieve the same error in a single prediction. Although radiolocation can be and is currently implemented with more precise approaches based purely on reflection (such as TDR or radar), some applications may require a different approach. The post-hoc tracking of Malaysian Airlines MH370 with an incidental dataset is one such case. This project establishes the viability of a system that utilizes differences in received power in place of exclusively reflected signals.

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