Synthetic Aperture Radar Imaging, Doppler, and Ranging Through Solids Using Frequency Modulated Continuous Wave Radar

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Abstract

Radar can be used to detect faint movements through dense material, map terrain through dense cloud cover miles above the earth, and calculate the distance from a point to an object. While regarded as a mature technology, Radar is by no means a dead field; current research includes detecting motion through walls, for search and rescue and law enforcement applications, detecting landmines, and consumer vehicle collision detection. We present here our work on the construction and testing of an extremely flexible yet inexpensive Frequency Modulated Continuous Wave (FMCW) microwave radar, based on MIT opencourseware, which is suitable for simultaneous range finding, synthetic-aperture imaging, Doppler-shift velocity determination and measurement of microwave absorptance of materials. Our Radar is constructed from off-the-shelf RF components, waveguide antennas made from recycled coffee cans, and interfaces with a laptop PC through its sound card, allowing us to perform digital signal processing and software visualization.

I. Introduction

Radar (Radio Detecting and Ranging) operates by transmitting electromagnetic radiation in the radio frequency band into the environment and then receiving the reflected signal. Different technologies and processes can be used to detect objects as well as determine range, speed, and even the shape of some surface.[1] The reflective properties of electromagnetic waves were first discovered by Heinrich Hertz around 1886 and within twenty years the technology had been advanced by Russian and German engineers to allow the detection of distant objects, namely ships at sea. The invention and refinement of the magnetron as well as looming war in Europe drove the early development of range finding radar systems.

The magnetron is a fairly complicated vacuum sealed microwave oscillator. It works by producing and accelerating an electron beam

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in an internal dc field that, once modulated, creates electron bunches that form a space wheel. The electrons then dispense their collected energy to the magnetron's internal AC field. We dissected a broken magnetron driven radar system that was gifted to us to better learn how older professional radar systems work. We discovered that, beyond the way that this system generates a wave and the antenna's enhanced design, this system operates similarly to our planned design. However, because of the magnetron's instability in its output, they are unsuitable for continuous-wave operation and must use a pulsed method of operation. Magnetrons themselves have largely been supplanted by klystrons and solid-state signal generators in smaller systems. It is now possible to fit an entire microwave-band radar on a single integrated circuit, making radar far more accessible, flexible, and inexpensive.

Determining distance with a pulsed radar simply requires measuring the time between a radio wave pulse's broadcast and its return, as radio waves propagate at the speed of light. Our system operates on a different principle; it is a Frequency Modulated Continuous Wave (FMCW) radar. A FMCW radar measures distance by transmitting a constant modulated signal. The reflected signal is then mixed with the transmitted signal and then decomposed mathematically to produce ranging information. Pulsed and FMCW radars excel at different applications. The benefits of a FMCW system in a project such as this are that it provides excellent low-range resolution, and is easy to construct. Our radar can also be operated in Continuous-Wave (CW) mode. The frequency modulation of FMCW mode cancels out the doppler effect, but using an unmodulated continuous wave enables the study of the Doppler shift of signals reflected by objects in motion. Our design is also capable of synthetic aperture radar (SAR) imaging, as well. SAR imaging entails taking multiple "snapshots" with the radar from slightly different angles in order to determine the shape of objects by comparing the change in depth. SAR will require slight movement of the radar on a predictable and stable track for best accuracy. This will be a great challenge, as even slight deviations from the proper path causes warping.[2]

We endeavor not only to rebuild the system for testing its explicitly intended purpose, but to also test its ability to penetrate materials and provide ranging, velocity, and even SAR imaging. "While it is not possible to see through walls by using visible light, it is possible by using larger micro-wavelengths to radiate into a wall and receive a weak scattered signal that is representative of what is behind the wall."[3]

II. Experiment

A. Materials and Apparatus

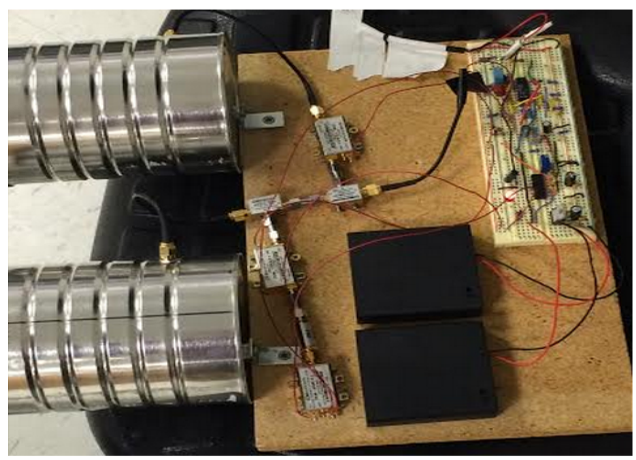

Figure 1: Final set-up of the radar

We followed the bill of materials from the course's syllabus and, for the most part, used the same components listed. All materials have been listed in the appendix. We found that there are a few things that should be added, fixed, or amended concerning the bill of materials. First, it should be noted that 6"SMA cables are not long enough to be connected in the way that is described in the fabrication instructions. The cables should connect to the can on its side about 1.8"from the base. The laptop that is used for this project must have a stereo microphone input and some form of recording software that can convert or encode the recording into .wav files. A copy of Matlab is required as well, but only for processing the .wav files. Testing the circuits requires the use of a function generator and an oscilloscope. The MIT procedure also calls for a network analyzer, which we did not have. The MAX414 quad op-amp called for in the bill of materials is out of production and difficult to find. We first attempted substituting a TL064ACN op-amp IC, but eventually acquired a MAX414. Finally, two 1.5"lengths of copper wire are required to connect to the microwave connector inside the cans. We used 12 gauge wire, as the exact width used in MIT's example is ambiguous. The length should be trimmed down gradually to about 1.2", or "until the measured reflection coefficient (return loss) is less than about -10 dB over the ISM band (2.4 to 2.5 GHz)."[4] As this is difficult to measure without a network analyzer, the length of our wire is approximate.

We began our build by assembling the RF stage. The VCO's output connects to the male end of the attenuator. The female end of the attenuator is connected to a barrel connector then to one of the amps. The output of the amp is connected to a barrel connector which connects it to the sum port on the splitter. The splitter required for the build has three ports labelled 1, S (meaning sum), and 2. The 1 port has a SMA cable attached that connects to the top of cantenna 1. The 2 port connects to the first input on the mixer. The mixer's second input has a barrel connector attached to it to connect it to the output of the second amp. The input of amp two connects to an SMA cable that attaches to cantenna 2.

The radar has two antennas; one to transmit, one to receive. The antennas connect to the radar's RF (radio frequency) stage. A voltage-controlled oscillator generates the microwave-band output signal, which is amplified and fed to the TX antenna (output antenna). This signal is also mixed with the amplified return signal, generating a "beat" waveform whose frequency is proportional to the range to target and is within the audio frequency range allowing us to record the signal to a .wav file and process it digitally. The distance between the transmittance antenna and the receiver antenna should follow the formula of

$P = (P_{(total)})/(4\pi R^2)$[5]

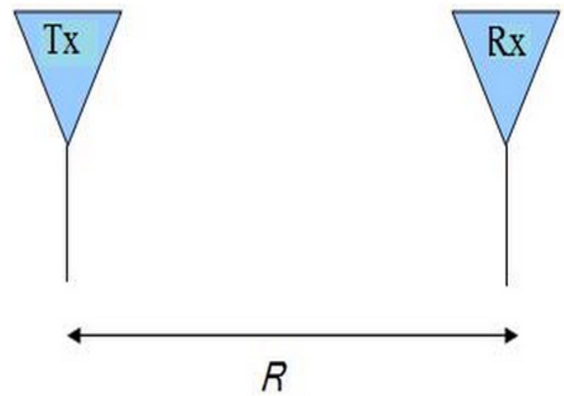

Figure 2: Transmit (Tx) and Receive (Rx) Antennas separated by R.

P will be the power density, and the R will be the distance between the two antennas. The antennas must be very carefully constructed. Two holes must be drilled into the base so that the cans can be mounted, using L-brackets, to the rest of the radar. A final hole must be drilled on the side of each can for the SMA antenna adapters to be installed in. We used a dremel tool to make precise and smooth holes in our cans. The two antenna should be as stable as possible so that the wave will not be affected by unwanted motion. We used washers between the can and L-bracket to keep the antennas stationary.

The rest of the circuits were built on a solderless breadboard. There are three sections: The power supply, the signal generator, and an output amp/active low-pass filter. The power supply consists of 8 AA batteries in series and connected to a voltage regulator IC, providing +5 and +12 volt lines. The signal generator circuit uses a function generator IC to generate a ramp wave that drives the VCO (voltage controlled oscillator). The output amp takes the sum of the TX and RX (receiving antenna) signals from the mixer and amplified them to be fed into a PC's sound card.

B. Methods and Procedures

This radar is supposed to operate in the industrial, scientific and medical (ISM) radio band of 2.4 GHz, emitting 10 mW TX power, at a maximum range of 1 km for 10 dBsm.[4]

An antennas gain is given by the formula

$G = 4\pi A/\lambda^2$

Where A is the effective aperture area. The gain will be different in our experiment due to the difference in form factor compared to the MIT example builds. This gain calculation will help us understand the maximum effective distance for our radar, once our antennas are repaired.

Effective isotropic radiated power (EIRP) is the measured radiated power in a single direction. It can be determined by the formula

$P_d(\theta, \varphi) = EIRP/4\pi r^2 = P_t G_t(\theta, \varphi)/4\pi r^2$

The analysis of wavefield physics using mathematics requires the use of the time Laplace transforms of EM field equations and quantities.[6] These transformations are certainly not too difficult to perform, but we instead opted to leave the mathematical heavy lifting to three Matlab scripts provided by MIT for this course. This programming allows us to view our recordings very quickly while testing, which allows us to test very rapidly while also removing the possibility for human error in mathematical calculation.

To test the radar we connect its 3.5mm audio cable to a computer's sound card and record. We used sound recorder on a laptop first, which gave lackluster results. When connected to a better soundcard, we found that there is far less interference in the recorded signal. We are considering using a mobile Protools 8 LE setup for the greatest accuracy next quarter.

III. Data and Analysis

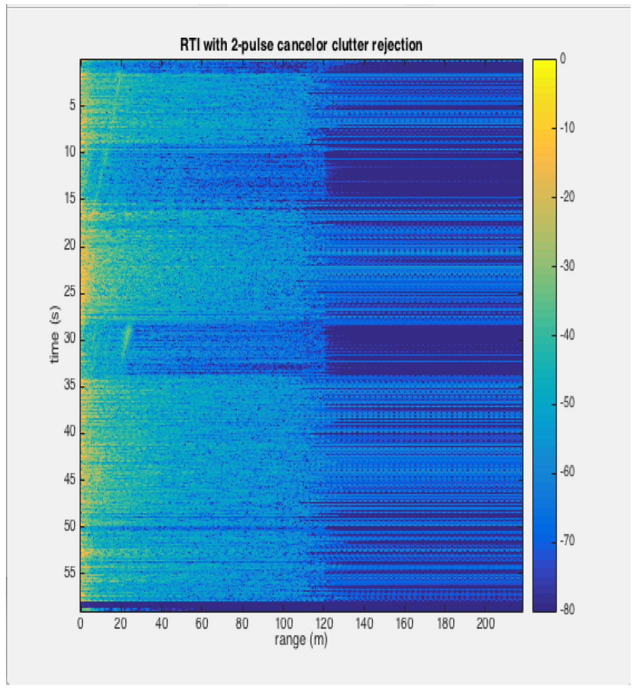

Figure 3: The graph of ranging test was conducted on the upper walkway between Brier and Alderwood by walking to and from the Alderwood entry.

The ranging appears to work correctly, albeit with a sizable amount of interference. The first test was conducted by walking the radar toward a glass door approximately 20 meters away. In the figure 3, the yellow diagonal line from about 0 s to 20 s is the trip to the door. We believe that the large number of light blue lines could be present due to the walls and handrails along the path. If this is the case, then the segment from 10 s to 15 s is likely less dense with blue lines due to the few feet on the path where there is no wall on the left or right of the path as you draw near to Alderwood. This is supported by the second period with less blue line density at the start of the return trip. The return trip begins with an estimated distance of 30 m, instead of 20 m, due to the depth of the stairwell behind our initial starting position. The blue lines may also represent noise in either the antennas or the computer?s microphone input. We tried several computers and each generated some amount of noise independent of the radar; the quality of our signal may be dependant on the quality of the analog-to-digital converters in the computer?s sound system.

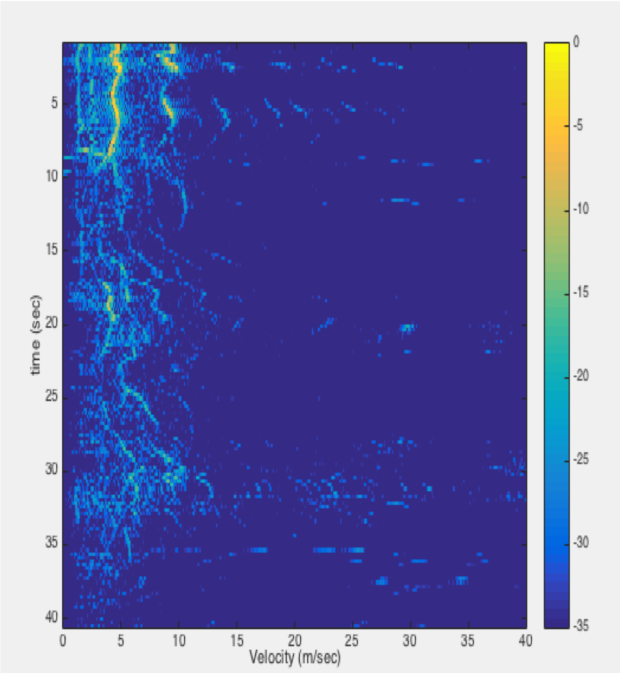

Figure 4: The graph of Doppler test was conducted at the corner of 200th St. and 68th Ave pointing north on 68th.

The CW mode Doppler data is far less conclusive. The speed limit on this stretch of road is 30 mph. We recorded 2 cars travelling roughly the speed limit away from us, 4 accelerating from slow right turns, and 3 experiencing negative acceleration. None of this is represented in Figure 4. This is likely due to antenna calibration issues. This is also evidenced by the ranging image, which should show the buildings we approached more distinctly, but their lines are quite faint.

The CW mode will require additional calibration and experimentation. When connected to an oscilloscope, the radar's combined output is easily recognizable, but our streetside test is indistinct at best. We may be experiencing added noise from the connected laptop?s audio input or induction noise from the audio cable we are currently using to connect to the computer. Our antennas are also not optimized and their ridged shape may affect their waveguide properties. Because the cables called for in the BoM are too short, the holes we drilled for our antennas are not in the correct position, and the antennas may not be optimally positioned with respect to each other in terms of rotation. We plan to find metal cans without ridges in the future to eliminate any noise that might be produced by the odd form factor, acquire longer cables, and maximize the input/output gain of our antennas.

Some improvement that we made for this quarter is doing a field division test. We tried to measure how far our radar works and how wide it is.

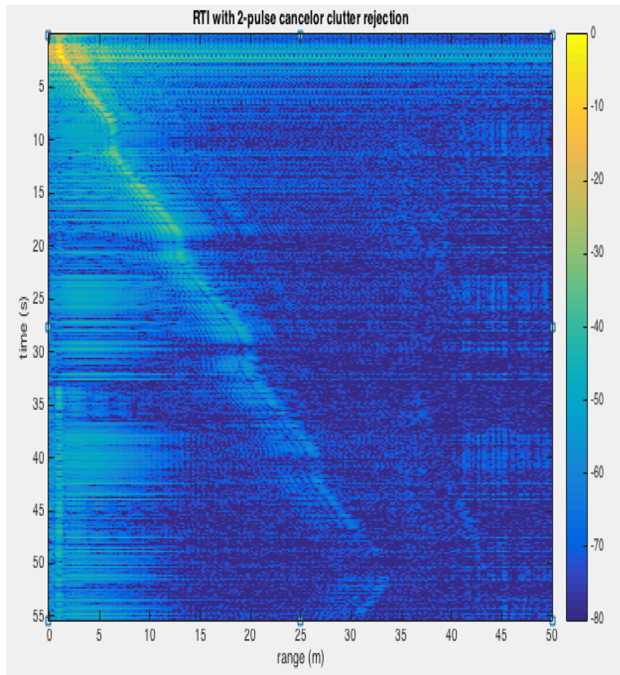

Figure 5: One people walking on the field

In this picture, one people of our group were walking further and further away from the radar. He stopped every 10 meters for about 2 seconds. That?s why there is vertical lines every 10 meters the object move because our radar read as the object stay at the exact distance for a couple seconds. After reach the furthest distance from the radar, object walked back approached the radar. Thus, we can se that is a vertical line with a negative slope at the bottom of the image.

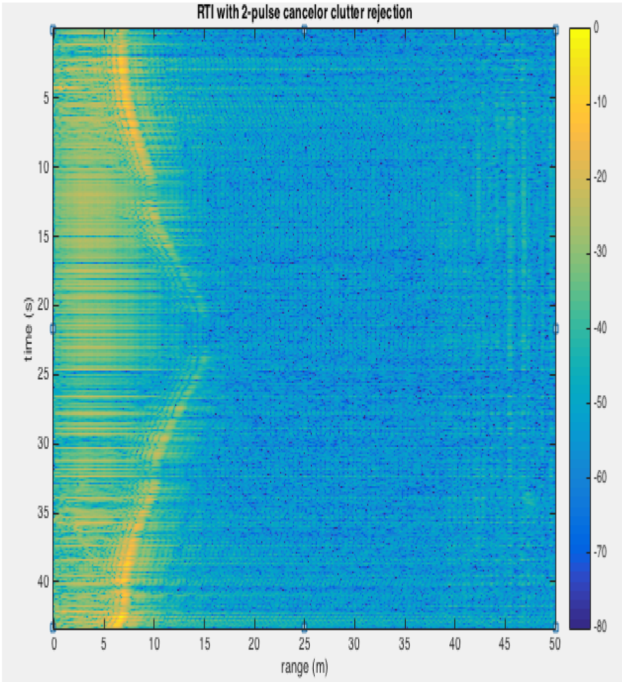

Figure 6: One person walking away and toward the radar

For this experiment, we test how wide our radar can actually works. One of our group stood around 5 meters away from the radar, and he moved laterally 20 meter to the right, and our radar still detect his movement. However, our radar read his position as 15 meter because our radar can only measure the length of the slope from the radar into the man?s position. And the people may not walk 90 degree straight from where he stood. However, it indicates that our radar has a very wide imaging ability.

IV. Conclusion

We've found a few flaws in our current design that, when fixed, will vastly increase our accuracy as well as our capability. In its current form, it could reliably sense the range of rather large objects up to at least 30 meters. It is currently difficult to interpret Doppler shift data given by the radar, but it does appear to be sensing movement as indicated by the slope of the two faint lines from our ranging data. There are very distinct waves when measuring the output of the LPF with an oscilloscope, which indicates that the muddied signal we are experiencing is some combination of the factors mentioned previously. Regardless of the current error levels we are recording, we are now poised to fine tune our build and produce abundant and accurate data.

V. Future Work

The radar needs to be recalibrated in a few ways. The cantennas need to be replaced with more perfectly cylindrical ones with four less holes in them. The monopole wire would need to be resized as well, to better fit the new cans. A better mounting system for the cans is necessary to prevent any unwanted movement that would skew results. It would be a good idea as well to add four padded feet to the bottom of the radar. A more long-term step would be to construct an enclosure for the radar and install the electronics on a printed circuit board.

We plan to test the SAR capabilities of our system by creating uniquely textured objects and comparing the SAR image to a picture taken at the same distance and follow those experiments with trials that are exactly similar except that we introduce some form of matter that visually obfuscates our target. We currently plan to use fog, smoke, cotton sheets, cardboard, and plywood to test the radar?s ability to penetrate matter. We will compare and determine their difference and similarity graphically.

We will also test the radar's ranging and velocity finding capabilities using far more precise methods. We will use an open stretch of road and drive at a given speed and compare the radars Doppler-shift analysis to the car's speedometer. We will then test smaller and smaller moving objects, made from different materials, to better understand what sorts of objects it may sense best. We will test its sensitivity over different distances by marking progressively further lengths, up to 1 km away from the radar and examining how the signal changes when an object moves further away. This data can be compared to the gain and EIRP values we derive mathematically.

Continuing coding for the raspberry pi. For now, we are using the MIT opencourse's matlab code to transfer the wave into the graph. Sometimes, it takes more than five minutes if the recording is long. However, if the raspberry pi is finished, then it will process the data faster and more clear. Also due to the time limited, we have not tested the Doppler Effect that much. In the future, we can test the velocity with the time change. Since we have improved the antenna and recording device, the data will have less echo. From that, the wave will show the velocity changing clearly.

VI. Acknowledgement

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- John Milner for donation of an old radar system
- Edward Lai for donating components and research materials.

VII. Appendix

A. Bill of Materials

- 2315-2536 MC VCO with +6 dBm Out
- 3dB SMA M-F attenuator
- two amps (Gain 14 dB, NF=1.2dB, IP1= 18.5 dBm)
- splitter (1900-4200 Mc, 0.1 dB insertion loss)
- mixer (13 dBm LO, RF to LO loss 6.1 dB, IP1 9dBm)
- four SMA-SMA M-M barrels
- three SMA-SMA M-M 6" cables
- 3.5 mm audio cable, stripped on one end
- two 4xAA battery packs
- resistors:
  - 8450 ohm 1%
  - 102K ohm 1%
  - 7150 ohm 1%
  - three 1K ohm 1%
  - 12.1K ohm 1%
  - 17.4K ohm 1%
  - 28K ohm 1%
  - 4120 ohm 1%
  - 1620 ohm 1%
  - two 5.1K
  - two 10K
  - 1K
  - two 100K
  - twelve 47K 5% resistors
  - 200 ohm 5% gain resistor
- function generator chip
- four 1000pf 5% capacitors
- 2M and a 50k trimmer potentiometer
- 10k trimmer potentiometer
- low-noise quad op amp
- 5V low dropout regulator
- 0.47 uf tuning capacitor
- 1 uf film capacitor
- breadboard

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