Designing a Narrowband Radar using GNU Radio and Software Defined Radio for Tomography and Indoor Sensing

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Abstract

This project achieved both high accuracy and low cost in a narrowband radar design by combining the unpopular Multiple Frequency Continuous Wave (MFCW) radar algorithm with the low-cost Software Defined Radio (SDR) on the GNU Radio platform. According to traditional Pulse or FMCW radar technologies, a typical SDR with 4MHz BW will have a theoretical accuracy limit of 3750cm (i.e. inaccuracy equivalent to the size of a large house). However, this project established the first SDR-based MFCW radar in the 2.4-2.5GHz band using two Continuous Waves (CW) with only a few kHz BW and a superior range accuracy of 15cm. Despite a lack of applicable publications on MFCW radar, a distance sensing algorithm capable of automatically correcting erroneous results from direct delta phase calculation was able to be created. This proof of concept opens the doors to many short-range radar applications using the emerging low power and low cost SDR technology. However, this project also revealed a non-linear phase issue that will need future improvement.

1. Introduction

Traditional radars were typically associated with high-power long-distance sensing over a range measured in kilometers. However in the last decade, lower-power radars with meter range measurements have become quite useful for autonomous vehicles, smart homes, medical sensing, imaging, and tomography for security with a "see through the wall" capability. The traditional "Pulse Radar" and Frequency Modulated Continuous Wave (FMCW) radar require about 1GHz bandwidth (BW) for 15cm resolution. This high bandwidth demand directly translates to high cost and high power, making it impractical for short meter-range indoor applications requiring centimeter accuracy.

1.1 Background Research on Traditional Radar Spatial Resolution

A traditional Pulse radar transmits a narrow electromagnetic pulse, and the reflected radio waves are detected by a receiver. The distance-sensing radar uses time-of-travel measurement to calculate distance based on the speed of electromagnetic wave (i.e. radio wave). As illustrated in Fig.1, the round-trip distance is derived from the product of time of travel and the speed of light. The round-trip distance divided by two can give us the distance of the object.

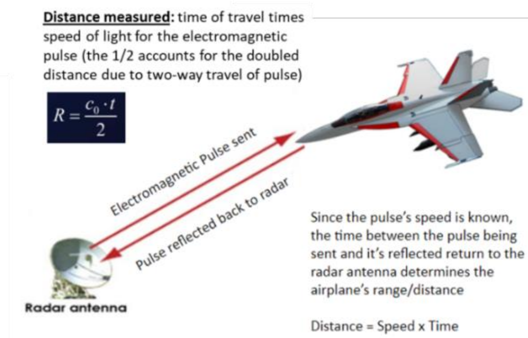

Fig. 1 Distance sensing radar is essentially measuring time of travel. [1]

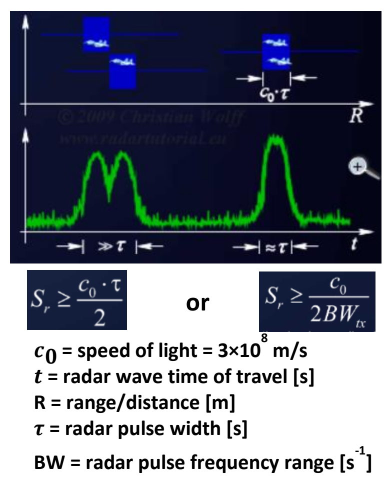

Fig. 2 Illustration for traditional Pulse radar distance sensing resolution determined by pulse width, and pulse width is a function of bandwidth. [1]

The distance sensing resolution is defined as the minimum distance between two objects where the radar can tell the two apart. As shown in Fig.2 with a pulse width of τ, two air planes with distance less or equal to τ times speed of light will look like a single air plane to the radar because the two returning pulses overlap. A wider bandwidth is required to produce a narrower pulse, so traditionally, the radar distance sensing resolution is inversely proportional to the radar signal bandwidth.

Another commonly-used distance-sensing radar besides the traditional Pulse radar is the Frequency Modulated

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Continuous Wave (FMCW) Radar. Instead of sending a single short pulse, the transmitter in an FMCW Radar system periodically sweeps its frequency from a lower to an upper bound. Bandwidth is the amount of the frequency band used. For such a system that uses all the frequencies between a lower and upper bound, the bandwidth is the difference between the bounds. The system uses the phase shift between the transmitted and received signals to determine the time of travel and calculate the distance. [2] [3] Although the signal waveforms are different, these two types of radar both rely on Ultra-Wide Bandwidth (UWB) to increase distance sensing accuracy. The disadvantages of using such a wide band include extremely high power consumption and harsh interference with other wireless devices, neither of which are tolerable for civilian use. Strict licenses are required to operate these kinds of UWB radar, effectively preventing amateur exploration outside the short license-free 2.4~2.5GHz citizen band. Thus, a different design must be implemented to work around civilian bandwidth restrictions.

1.2 Software Defined Radio (SDR)

Software Defined Radio is an active research area featuring a software-configurable hardware and enabling users to construct Radio Frequency (RF) systems through software. While an RF circuit design requires advanced college-level engineering knowledge, the SDR platform enables any amateur to explore any RF system with transmit and receive capabilities, including walkie-talkie, satellite receiver, and even Doppler radar. All these systems can be constructed through software codes. [4] Therefore it is an ideal platform for this new radar algorithm research through coding changes rather than rewiring.

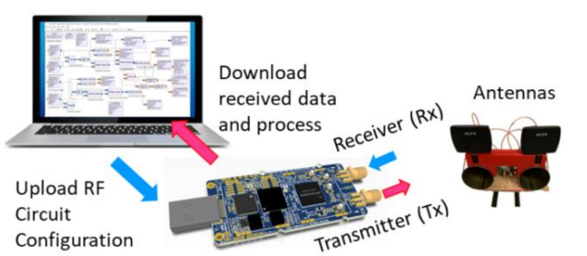


Fig. 3 Developing a radar algorithm prototyping platform using low cost SDR from crowdfunding based LimeSDR mini.

As shown in Fig.3, a very low cost (<$200) SDR transceivers that was purchased from LimeSDR's crowdfunding website is used for this project. Of course, the disadvantage is that the low cost LimeSDR mini is still a work-in-progress with many bugs and very limited documentation. Some of the challenges and limitations will be described in the following sections.

Several publication and implementation can be found of SDR-based Doppler radar, which is a very narrow-band single-frequency radar that can only provide speed information of the object without distance information. The main reason for this limitation is because of the limited bandwidth of a typical SDR system at only about 10MHz ~ 20MHz. Based on personal experimentation with LimeSDR mini, even at just 4MHz and above, the computer interface gets saturated and occasional drop data samples. For a typical SDR with 4MHz BW, it will have a theoretical accuracy limit of 3750cm (i.e. inaccuracy equivalent to the size of a large house). [1] Therefore it may only be useful for detecting large object far away such as an airplane or a ship. To reach distances that far, a radar would need to transmit in very high power. SDR units are typically a very low power design for short distance transmissions. Attempts to amplify the signal to high power are restricted by the FCC's one-watt transmission limit even in the license-free 2.4~2.5GHz citizen band. That is the fundamental reason why no one is able to showcase an SDR-based radar to measure distance.

However, there is clearly a strong demand for lower-power radars with meter-range measurements for use in autonomous vehicles [3], smart homes [5], medical sensing [6], imaging [6], and tomography for security with "see through the wall" capabilities [7]. That is the motivation behind this project – a feasibility study of an SDR-based, narrow-band, low-power radar technology capable of distance sensing in meter range while maintaining a reasonable accuracy. Such technology could be widely used for the short distance applications listed above.

1.3 Narrow Band Distance Sensing Technology (MFCW)

Extensive research for a legal way to explore the amazing radar distance sensing capability uncovered an unpopular Multiple Frequency Continuous Wave (MFCW) radar algorithm.[8] The bandwidth requirement was as low as kHz range. The key realization of this project was that the low-bandwidth MFCW radar algorithm paired with a low-cost, low-power SDR system would meet all the requirements for a meter-range, centimeter-accuracy radar. Because the general lack of applicable publications on MFCW radar, no actual implementation examples of MFCW radar using Software Defined Radio (SDR) exist.

The main challenge for this project was to create a distance-sensing algorithm with the SDR in hand. As shown in the following sections, an algorithm capable of automatically correcting erroneous results from direct delta phase calculation has also been developed as the result of this research. It provides a new promising direction for achieving both high accuracy and low cost with a narrowband radar design by combining the unpopular Multiple Frequency Continuous Wave (MFCW) radar algorithm with the low-cost Software Defined Radio (SDR).

As shown in Fig.4, the MFCW radar uses two or more frequencies of Continuous Wave (CW) simultaneously instead of a pulse. Distance is calculated from the phase difference between the two CW signals, so it is an extended type of interferometry radar relying on phase measurement. Fig.4 shows an MFCW radar operating with two different CW frequencies with different wave-length. At specific distances, the phase difference info for each of the frequencies is uniquely determined. Using the known frequency difference, Δf, and measured phase difference, ΔØ, the distance can be calculated.

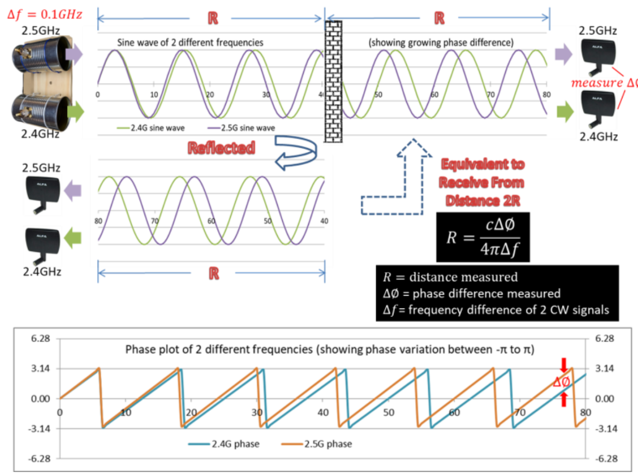


Fig. 4 MFCW radar operates with two different frequencies of CW waves with slightly-different wavelengths. For a specific distance, the phase difference between the two frequencies is used to determine the distance of the object.

The phase plot of the two frequencies in Fig.4 showed triangular curves with the phase linearly increase between –π to +π as a periodic function. Since the phase is a modulo of 2π, the range becomes ambiguous when $\Delta\emptyset = 2\pi m$, where m is a positive integer. The <u>maximum unambiguous range</u> occurs when m=1, with c being the speed of light: [8]

$$R_{max\_unambiguous} = \frac{c}{2\Delta f}$$

For a 2.5GHz wave (wavelength= 12cm) and a 2.4GHz wave (wavelength=12.5cm), the phase will line up again after a 300cm round trip, because 25x12cm=24x12.5cm=300cm. Therefore, the MFCW radar maximum unambiguous range is 150cm with the 2.5GHz and 2.4GHz. Using 2.5GHz and 2.45GHz will double the max range by reducing the Δf.

The advantage of MFCW is the super low bandwidth requirement of less than even 1 MHz. This is because it only requires two small slivers of bandwidth at specific frequencies as opposed to a whole range of frequencies. However, MFCW radar requires multiple RF transmit and receive channels with stable phase relations.

2. Research Question

While a distance-sensing radar's high resolution of 0.15m is traditionally achieved with ultra-wide 1GHz bandwidth, can a radar be made to have comparable resolution using a Software Defined Radio (SDR) with only a 2MHz bandwidth, which is over two magnitudes lower?

3. Hypothesis

If an MFCW radar can be made with a low-cost and low-power SDR unit with merely 2MHz bandwidth, it will be able to achieve the superior ~0.15m distance sensing accuracy of an expensive traditional "pulse radar" or FMCW radar with ultrawide 1000MHz bandwidth.

4. Design #1: <u>Single SDR Multi-Frequency-CW</u>

4.1 Procedures and Algorithm

The project started with an aggressive design concept, which attempted to use a single SDR to source and capture the multiple frequencies required in an MFCW radar. The concept, as illustrated in Fig.5, is that the transmit(TX) port and the receive(RX) port connected to the SDR periodically "hop" between two frequencies, eliminating the seemingly-unnecessary cost and power of multiple physical channels. Two phase measurements are done on two different frequencies using the same hardware (TX, RX, and SDR).

The transmit frequency is selected in the 2.4~2.5GHz ISM frequency band not only because it is in the "citizen band" without any license required to operate, but also it is able to penetrate walls and skins for medical imaging and through wall tomography applications.

Before trying to create a new complicated MFCW SDR radar algorithm, a simple SDR-based Doppler radar was made using a reference design found on the internet. This design by Luigi Freitas has one TX port to transmit the radar signal and one RX port to receive the reflection. [9] The idea behind the Doppler Effect is that if the object being measured is moving, the received reflected signal will have changed in frequency. This lets Doppler measure speed, but not distance. Nevertheless, it provided a simpler radar development platform to learn hardware wiring and software controls.

Luigi's project was traced back to an MIT Open Courseware source with a lot more details on theory and design of the "MIT Coffee Can Radar" concept, although the MIT project hardware design is more complicated and not SDR-based. [11] While this project leverages the antenna design from this MIT project and the basic software example from Luigi's project, its main focus is on expanding narrow band SDR radar's capability to include distance sensing with comparable accuracy to the ultra-wide-band radar with 1GHz of bandwidth. This improvement relies on introducing the phase detection algorithm with MFCW concept to the SDR world as proposed in Fig.5. A 2kHz signal modulated on a 2.5GHz carrier is transmitted. The phase ϕ_1 of the received 2.5GHz+2kHz signal carries the info of distance R. After the demodulation, the phase ϕ_1 with distance R is transferred to the received 2kHz signal. The same operation is done with 2.4GHz carrier. Then, the distance R is derived from Δf and $\Delta\emptyset$. [8]

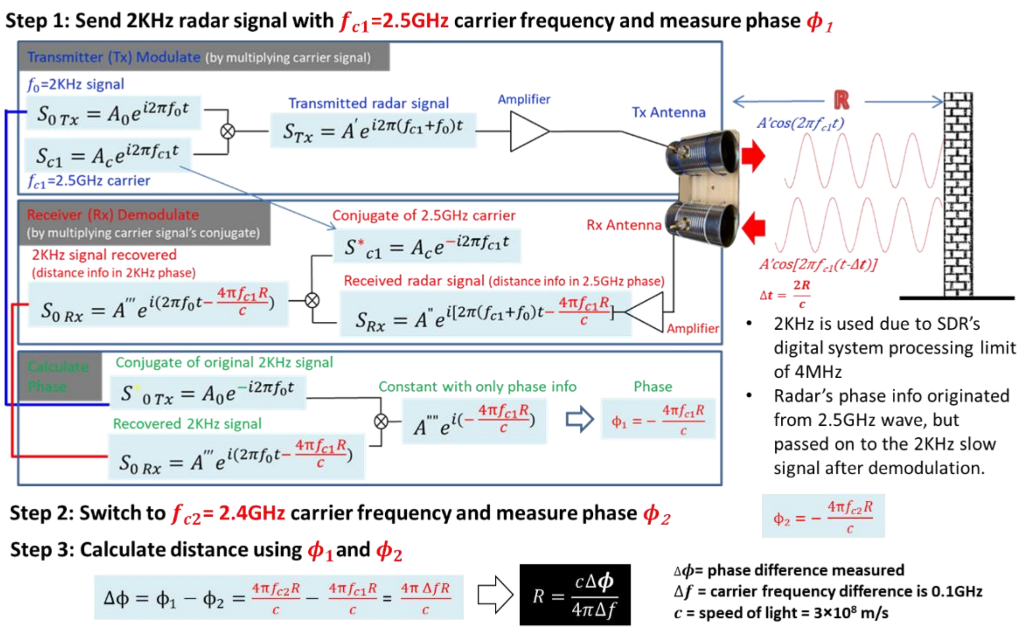


Fig. 5 A single-SDR Multi-frequency design concept illustration.

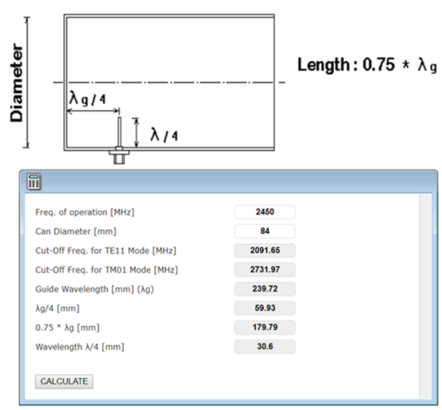


Fig. 6 Screenshot of free calculator [10] used to determine optimal coffee can dimensions for the operating frequency range

4.2 Materials

The tin can antenna design dimensions is shown in Fig. 6, which is optimized for 2.45GHz operation, which is centered between the two operating frequencies (2.4 and 2.5GHz). Two baked bean tin cans were selected with 84mm diameter, and two N-Type female connectors are used to hold the quarter wavelength monopole wire as the radiating source in the tin can. [10]

The full experiment platform to study radar with centimeter resolution requires a reliable setup with accurate distance control. As shown in Fig.7, this is by mounting the target on a camera slider rail. The radar is mounted at a fixed location on the camera slider. The Lime SDR's transmit port is connected to one antenna with a coaxial cable, and the receive port is similarly connected to the other antenna. The radar must first be calibrated by setting the target at a fixed position and "zero-ing" the transmit and receive to be perfectly aligned in phase. All distances are measured from this zero point, which was set at 30 cm from the ends of the TX/RX cans.

The software platform used to write the program for the SDR is an open source freeware – GNU Radio Companion version 3.7 for Windows. The program is developed in an intuitive GUI interface with a minimum learning curve to start programming algorithms in a data flow chart manner. The new MFCW SDR radar code developed is shown in Fig. 8. When compare to the conceptual design shown in Fig.5, this block diagram styled GNU Radio code looks essentially identical with various mathematic operations encapsulated in functional blocks such as Signal-Source, Modulation, Demodulation, and Multiply-conjugate phase measurement.

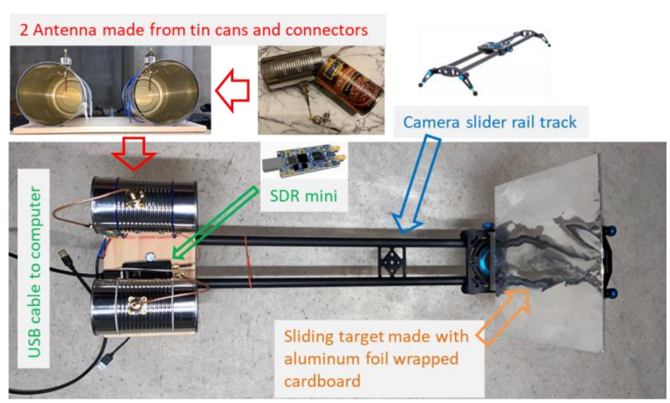


Fig. 7 Single SDR radar system developed for analyzing distance with a target mount on a camera slider rail.

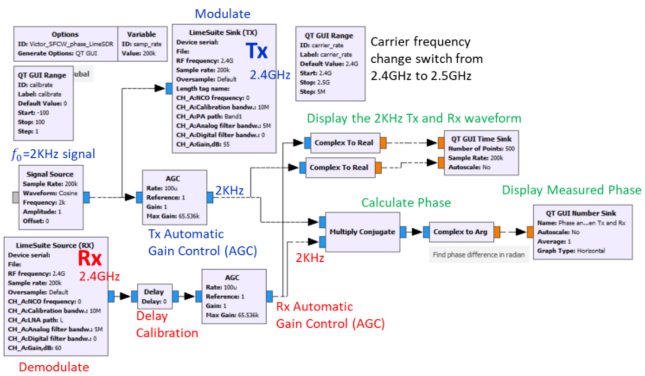


Fig. 8 New MFCW SDR Radar software developed with single SDR equipped with manual frequency switch between the two frequencies (2.4GHz and 2.5GHz).

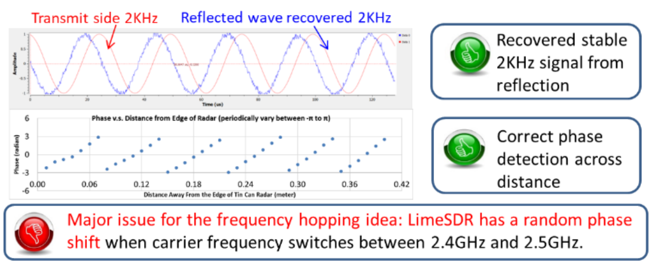


Fig. 9 Test results for single SDR MFCW radar showing stable signal detection and phase calculation at single frequency. However, LimeSDR hardware could not keep the phase stable during frequency switching.

4.3 Test Results and Data Analysis (Single SDR)

The test result for this single SDR equipped with manual frequency switch was only partially successful. The 2kHz sine wave radar signal was successfully transmitted on the 2.4GHz and 2.5GHz carrier frequencies, and the signal reflected from the target was successfully received. The new radar phase measurement capability at a single carrier frequency worked perfectly, as verified by incrementally sliding the target to increase the distance on the camera slide, as shown in Fig. 9.

However, a LimeSDR mini hardware issue marks this “frequency hopping” design a failure. The LimeSDR unit has a random starting phase when the carrier frequency is switched. In other words, when first used in 2.4GHz, we calibrated the distance to zero and measured phase accurately without a problem, but once switched to 2.5GHz and back, the original phase calibration is lost. Because phase stability is crucial for MFCW, this random phase shift while switching frequencies prohibits the single SDR design, as the zeroing point for both frequencies is lost in the switching process. Before an appropriate stable-phase SDR is found, the alternative is a revised design using two SDRs, one at each frequency, to eliminate the switching requirement.

5. Design #2: Dual SDR Multi-Frequency-CW

5.1 Procedures and Algorithm

In order to keep the phase calibration for each frequency, the new design used two LimeSDR mini’s, one operating at 2.4GHz and the other at 2.5GHz. This design improvement is used as a work-around for the phase shift problem of LimeSDR mini in the last design. Without any frequency switching needed after initial power on calibration, the phase measurement becomes repeatable.

The Dual SDR radar system software in Fig. 10 can be partitioned into two nearly independent sections for two SDRs. They are essentially duplicated from the existing single SDR phase measurement coding. The two sections are connected by a shared 2kHz signal source to synchronize the two SDRs and a subtraction between the two phase measurements from the two SDRs to get the phase delta, and finally target distance calculation.

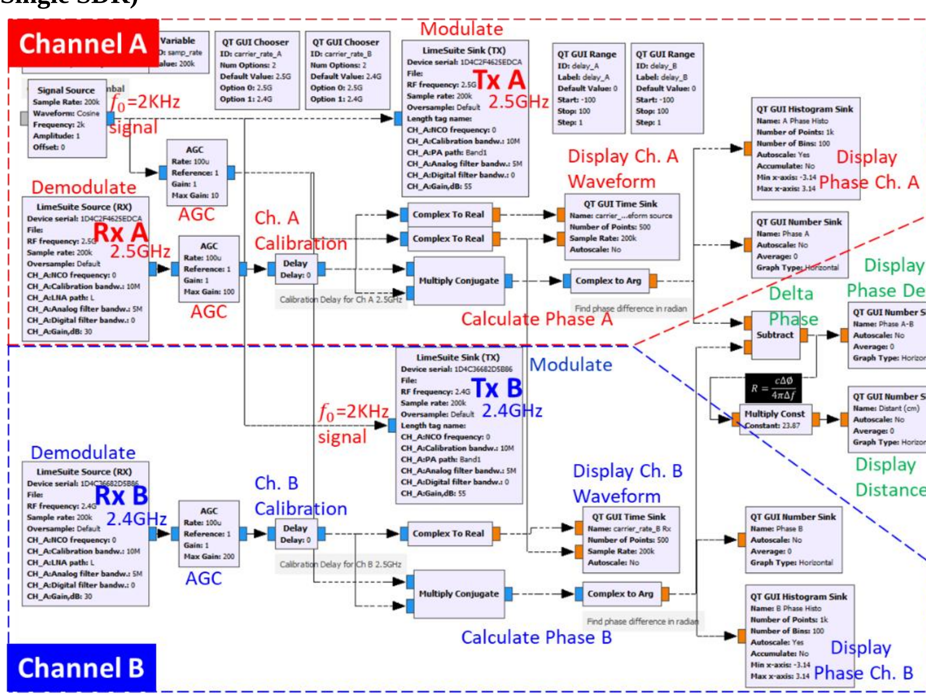


Fig. 10 Dual SDR MFCW radar system software was developed by duplicating the existing single SDR phase measurement coding, plus a phase delta and distance calculation logic.

5.2 Materials

The second SDR needed a pair of antennas for transmit and receive as well. In order to minimize the increase in size, two compact directional 2.4GHz panel antennas were added as receivers. These are commercially available for WiFi and drone applications. As shown in Fig.11, the panel antennas are much smaller than the tin can antennas. The two tin can antennas are better kept as transmitters because of their higher directionality, which can direct more of the energy towards the target in the front without coupling into adjacent antennas.

Stably mounting the swivel antennas on top of the round cylindrical cans was a challenge. A custom made antenna bridge was made using 3D printing with PLA plastic. The bridge shown in Fig.11 illustrates the functions of this bridge not only to hold the four antennas together but also to provide some distance between antennas to reduce the magnetic coupling between adjacent antennas.

In the GNU Radio software, a real time GUI interface was developed for debug and demonstration purposes. It not only displays the final distance sensing result but also displays some of these intermediate calculations and even the waveforms and phase movement, as shown in Fig. 12.

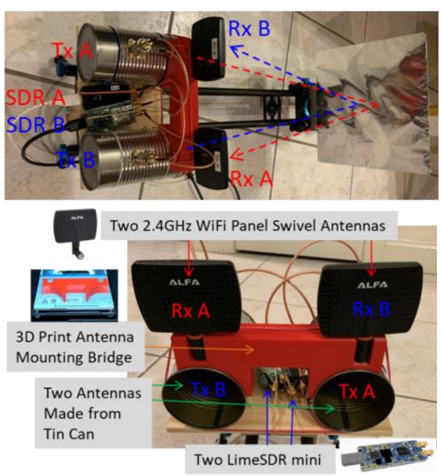


Fig. 11 Dual SDR radar system developed with two WiFi panel antennas added on top of a 3D-printed mounting bridge.

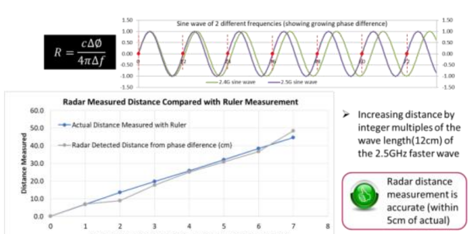


Fig. 13 Preliminary test result for dual SDR MFCW radar by set the target distance at special locations that is integer multiples of the wavelength (12cm) of the 2.5GHz wave demonstrated <5cm error from the distance measured with rulers.

Before any advanced algorithm is developed, the quickest way to evaluate if the phase difference measured really reflect the target distance was set the target distance at integer multiples of the wave length (12cm) of the 2.5GHz (i.e. the faster wave with shorter wavelength). As shown in Fig. 13, the phase of the 2.5GHz wave is always zero at these special locations. Then, the delta phase is simply the phase measurement of the 2.4GHz wave, minus zero. Using the distance equation found in reference [8], this calculated distance showed strong correlation to the actual distance measured using a ruler. The maximum error is less than 5cm. In other words, the accuracy is a fraction of the 12cm wavelength, which is the clear advantage for MFCW as a type of interferometry radar relying on phase measurement. Other pulse and FMCW radar algorithms will have accuracy larger than the wavelength used.

5.3 Develop Algorithm for Arbitrary Distance Calculation

Although preliminary data from setting the target distance to integer multiple of the wavelength demonstrated the potential superior accuracy of this MDCW's radar design, it is not realistic in real radar applications in which target can be located at arbitrary distance. As a simulation, the phase, phase difference, and calculated distance are plotted over target distance as illustrated in Fig. 14. This highlighted an issue where the simple equation give in reference [8] can create impossible negative values for the calculated distance in specific ranges. These erroneous results required an improved algorithm to use the radar at arbitrary distance.

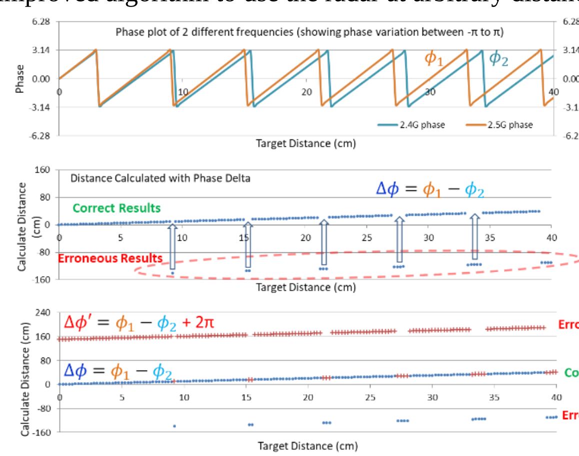


Fig. 14 The process of identifying the erroneous result in existing MFCW distance sensing algorithm and developing correction techniques to enable arbitrary distance sensing. Each signal's phase as a periodic function of distance forms a sawtooth wave from -π to π, the erroneous distance calculation will show up when $\phi_1 < \phi_2$, lowered by the amount of 2π.

Analysis revealed that erroneous phase difference results were actually just lowered by the amount of 2π, which caused the calculated distance to be negative. The improvement to this algorithm as a result of this project is adding 2π to the phase when the erroneous result occurs. As shown as the bottom plot of Fig. 14, when the corrected phase difference is used, the distance reported will become a linear straight line. In other words, the phase correction created in this project patched up the "holes" in the radar distance sensing range. When $\phi_1 \geq \phi_2$, it calculates the delta phase regularly with $\Delta\phi = \phi_1 - \phi_2$, and if $\phi_1 < \phi_2$, it uses the correction algorithm, $\Delta\phi' = \phi_1 - \phi_2 + 2\pi$.

5.4 Test Result and Data Analysis (Dual SDR)

The procedure used to testing radar accuracy was done by moving the target from 30cm to 70cm away from the antenna in 1cm increments. As shown in Fig. 15, the data points in blue indicate calculations from the original equation, and the points in red indicate erroneous phase corrected with the improved algorithm, which would otherwise give impossible negative values for distance. The straight green line is the ideal distance measured with a tape measure glued on the camera sliding track (measured starting at the calibration zero-ing distance of 30cm). As you can see, this dual narrow band SDR MFCW radar design has a distance measurement accuracy of 15cm within a 70cm range. However, the measured distance showed periodic oscillation, with degrading accuracy as distance increased, which seems to indicate an undesirable systematic error.

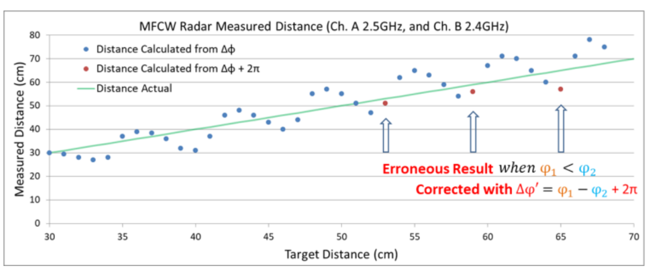


Fig. 15 Test result of the dual-SDR MFCW radar for distance sensing of a target moved from 30 to 70cm away from the antenna in 1cm increments. Blue points indicating calculation from the original equation, and the red points indicate erroneous phase results corrected with the improved algorithm.

To better understand this systematic error and possibly resolve it, the actual phase measured from 2.5GHz signal (see Fig. 16) was recorded. Instead of a theoretical linear triangular phase-over-distance curve, a non-linear curve was observed in the actual signal's phase. The periodic variation in phase explains the sinusoidal error observed in Fig. 15. This is likely a result of non-linear amplifier phase.

Since this nonlinear phase is a property of the SDR used, no good solution could be found to correct it. By using a different pair of frequencies (i.e. 2.5GHz/2.45GHz), which changes the Δf from 100MHz to 50MHz, and adding a 2.5kHz digital filter in SDR, it introduced yet another different nonlinearity into the system. As shown in Fig. 17, the result is an improved long-range accuracy and much worse accuracy near the radar.

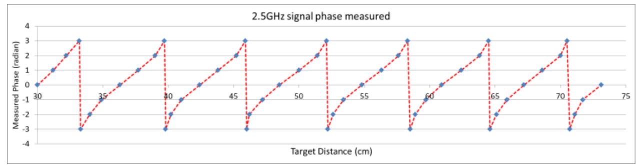


Fig. 16 Non-linearity observed in signal phase (likely result of non-linear amplifier phase). Ideally, it should be linear sawtooth waves.

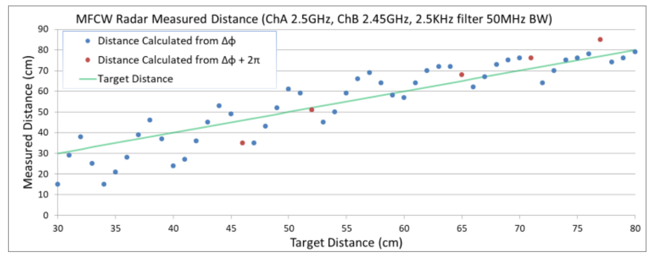


Fig. 17 Improved long-range accuracy but degraded short range accuracy by using a different pair of frequencies (i.e. 2.5GHz/2.45GHz), which changes the Δf from 100MHz to 50MHz; adding a 2.5kHz digital filter in SDR; and moving the target from 30~80cm in 1cm increment.

As future research, a mathematic model could potentially be created to correct this nonlinear phase behavior. However, this MFCW radar's 15~20cm accuracy is already incredible considering its SDR can only provide a 4MHz bandwidth. Using other algorithms, such as pulse and FMCW, would give this SDR radar a much worse theoretic range resolution of 3750cm.

6. Tomography and Short Distance Sensing Applications

A low cost SDR radar achieving distance sensing accuracy in the 15cm resolution can enable many short meter-range radar applications for autonomous vehicles [3], smart homes [5], medical sensing [6], imaging, and "see through the wall" tomography for security [7]. In other words, it can be considered a replacement for the existing more expensive and higher power UWB radar requiring a 1GHz bandwidth.

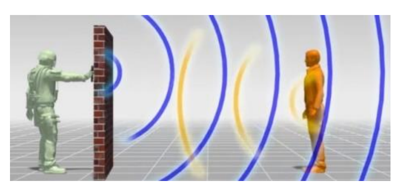


Fig. 18 Radar tomography gives cops ability to 'see' through walls

The ability to "see through the wall" and detect moving humans is very useful in helping law enforcement officers avoid walking into an ambush and minimize casualties in hostage rescue missions. Emergency responders can also use it to see through collapsed buildings and locate survivors. As a trial run for the end application, the ability of this SDR MFCW radar was tested for "See-through-the-wall" tomography (Fig. 18). [12]

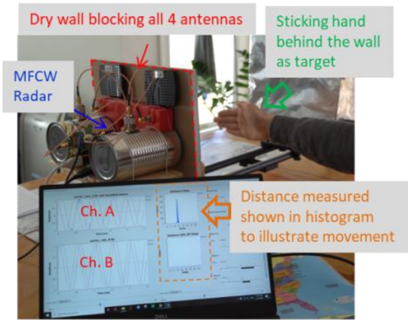
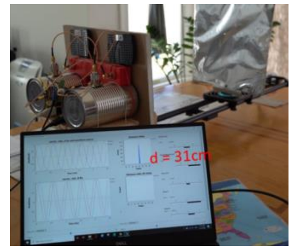


Fig. 19 The tomography capability is demonstrated by placing a piece of drywall in front of all 4 MFCW radar antennas. A hand is used as a moving target behind the obstacle.

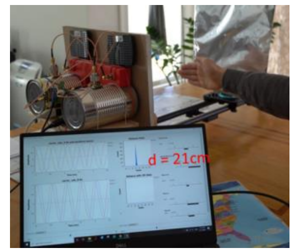
As shown in Fig. 19, the tomography experiment is demonstrated by placing an obstacle — such as a piece of drywall, a piece of wood, or a water jug — in front of the MFCW radar. A hand was used as a moving target behind the obstacle. The GNU Radio program developed for this project uses a histogram to display recent distance measurements, which emulates a standing human and serves as an excellent visualization of the target behind the "wall". The pictures shown in Fig. 20 include 3 different scenarios: (a) a static histogram indicating no object moving behind the wall; (b) a changed histogram location detecting a human entering the room behind the wall; (c) a smeared out histogram bearing a signature of a fast-moving object behind the wall. The histogram refresh rate can be adjusted to detect a desired speed range shown as "fast moving".

These tomography experiments demonstrated the ability of a 2.4~2.5GHz radar to penetrate drywall, wood, water and oil, making it a good candidate for both security and medical tomography. More importantly, this tomography radar is achieved with merely 4kHz bandwidth instead of the traditional tomography radar requiring ~1GHz to get a comparable resolution for short distance applications in the range measured in meters instead of kilometers.

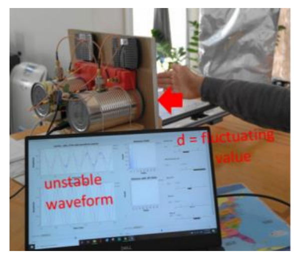
However, the phase nonlinearity induced systematic sinusoidal error in distance sensing, as shown in Fig. 15 and Fig. 17, created an undesirable artifact. This MFCW radar system cannot distinguish the direction of the movement. Even if the hand is monotonically moving towards the radar, the "oscillation" in distance error from positive to negative will make the histogram move back and forth while approaching, as if the object behind the wall is taking a few steps forward and then a step back. In future research, if this phase nonlinearity can be removed either through better SDR hardware or software compensation, this MFCW radar should be able to distinguish the direction of motion of objects behind the wall.



(a) Background reflection (before placing hand behind the wall)



(b) Detected a target slowly moving in, with histogram position changed (indicating a moving "human/object" behind the wall)



(c) Detected a fast-moving target with the histogram smearing out as result of recorded target location history.

Fig. 20 The GNU Radio program developed uses a histogram to display the distance measurement, which emulates a standing human behind the wall. The "visualization" of the moving target behind the wall is reflected as histogram movement.

7. Conclusion

In conclusion, the first SDR-based MFCW radar in the 2.4-2.5GHz band was made with range accuracy of 15cm while only using a few kHz BW and two continuous waves. A self-made distance sensing algorithm was also created with capability to correct erroneous results from direct delta phase calculations. In comparison, a traditional Pulse or FMCW radar would have to use 1GHz BW to achieve the same 15cm accuracy. This project demonstrated a new approach in making the narrow band radar more accurate and low cost by combining the unpopular MFCW radar algorithm with the low cost SDR, which can lead to many useful short range radar applications.

However this project also revealed several hardware issues with the SDR used, which can help improve the emerging SDR technology.

8. Future Research and Benefits

Future research will focus on the two issues identified and prepare the SDR-based MFCW radar for real world applications. First, the random starting phase issue in the single-SDR frequency hopping design could be resolved with an advanced loopback calibration before every phase measurement. As for the inaccuracy due to the non-linear phase issue, a linear external Automatic Gain Control (AGC) circuit can be used to avoid driving the SDR's built-in AGC circuit into the high gain and nonlinear phase range. With more advanced antennas, 2D or 3D radar imaging can be developed for medical and security applications, beyond 1D distance sensing.

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