Penetrating Radar Combined With 3-D Imaging for Real-Time Augmented Reality Sensing and Classification

Joshua Girard[a], Dylan Burns[b], Dryver Huston[c], and Tian Xia[d]

[a,b,c]University of Vermont Department of Mechanical Engineering, 33 Colchester Ave, Burlington, VT

[d]University of Vermont Department of Electrical and Biomedical Engineering, 33 Colchester Ave, Burlington, VT

ABSTRACT

This paper presents research on the use of penetrating radar combined with 3-D computer vision for real-time augmented reality enabled target sensing. Small scale radar systems face the issue that positioning systems are inaccurate, non-portable or challenged by poor GPS signals. The addition of modern computer vision to current cutting-edge penetrating radar technology expands the common 2-D imaging plane to 6 degrees of freedom. Applying the fact that the radar scan itself is a vector with length equivalent to depth from the transmitting and receiving antennae, these technologies used in conjunction can generate an accurate 3-D model of the internal structure of any material for which radar can penetrate. The same computer vision device that localizes the radar data can also be used as the basis for an augmented reality system. Augmented reality radar technology has applications in threat detection (human through-wall, IED, landmine) as well as civil (wall and floor structure, buried item detection). For this project, the goal is to create a data registration pipeline and display the radar scan data visually in a 3-D environment using localization from a computer vision tracking device. Processed radar traces are overlayed in real time to an augmented reality screen where the user can view the radar signal intensity to identify and classify targets.

Keywords: Augmented Reality, Penetrating Radar, Localization, Computer Vision

1. INTRODUCTION

Penetrating radar is a well established field. There are methods to scan and process data in order to identify buried or obscured structures. An issue with the current methods however is that they are relatively rigid, meaning that they are constrained to 2-D planes or localization using wheel encoders that can be disturbed by irregularities in the ground or scanning surface. Often, they take post processing and a highly trained eye to identify a target and its location.[1] The goal of this research project was to generate a system that is efficient, easy to use, fast and effective in allowing the user to identify hidden targets in radar permeable mediums.

This research combines the fields of radar technology and signal processing, with computer vision and pose measurement. Both of these fields have established methods for scanning and recording data, but it is the union of the two where the work is to be done. Penetrating radar is a field of electronic imaging and sensing which relies on the different permeability and reflectivity of different materials to EM waves. Throughout this paper, the terms 'A-scan' and 'B-scan' will be used. The A-scan refers to a single 1-D radar trace, where each point at distance x from the radar anntenna has power I and a B-scan is a horizontal concatenation of A-scans which is used to view 2-D cross sections of a scanning site. Figure 1 shows the A scan, power vs. distance, and the B scan, power vs. distance repeated over a second dimension.

Further author information: (Send correspondence to J.G.)
J.G.: E-mail: joshua.girard@uvm.edu, Telephone: 1 802 377 1747

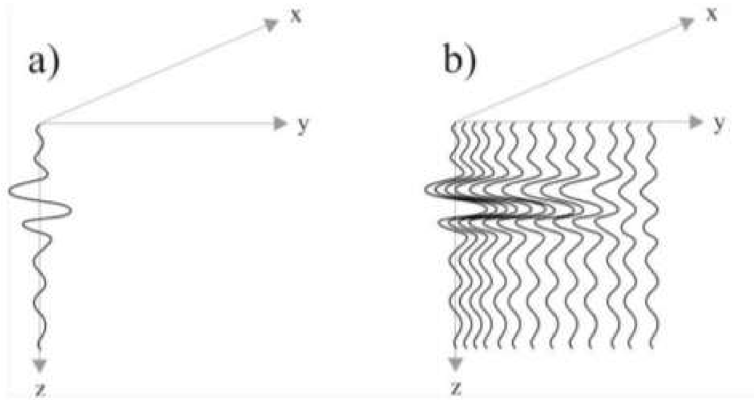


Figure 1: A conceptual depiction of A and B scans for data visualization.[2]

For the most part, processing the aforementioned types of scans does not happen in an augmented/mixed reality scenario. There are some applications that allow the user to explore 3-D radar data in mixed reality however,[3] and it is on this research that this program is designed to build.

2. MATERIALS AND HARDWARE

The basis of this system is a handheld radar transmitter/receiver with a software development package. This comes in the form of a handheld product called a 'Walabot'. The Walabot is nominally a wall penetrating radar with limited signal strength but it is easy to interface through USB connections and pre-made code libraries. It has 18 Tx/Rx pairs which operate in the 7Ghz range, which supports a variety of live wall scanning applications. Only 1 Tx/Rx pair is used for this project, since a single trace per location is desired.

For computer vision, there is a device called the 'Realsense T265 Tracking Camera' made by Intel. The T265 has an internal IMU along with 2 fisheye camera sensors. This device works by combining the IMU accelerations (rotational and translational) with the camera feed in order to generate a pose accurate to about 1cm. The camera feed negates any electronic drift from the IMU.

3. SOFTWARE AND LIBRARIES

In order to integrate the two devices and make a functional augmented reality program, they were all interfaced using Python 3.6. The Walabot is interfaced using USB and a custom API made by Vayyar Systems (makers of the device) which is called 'WalabotAPI'. The T265 was also connected via USB and interfaced with a library called pyrealsense 2.0. The image processing library used to handle the camera feed and display radar overlay is OpenCV for python (pyopencv). Documentation and resources for these three libraries are listed in the reference section.[456]

4. METHODS

4.1 Computer Vision and Position Tracking

The radar data localization is based on quaternion rotations. Quaternions are a 4-D representation of a rotation where the x, y, and z components represent a directon in 3 space, and the w component is the rotation angle in radians about the direction specified, see Equation 1. The advantage of this rotation representation is that there are no singularity points and the T265 which is calculating pose will never experience issues with gimbal lock.

$$q =< x, y, z, w > \tag{1}$$

The most important mathematical quality of quaternions used for this project is that they can be used to rotate a vector $v =< v_1, v_2, v_3 >$ as follows in Equation 3 where p is a quaternion equal to $< v_1, v_2, v_3, 0 >$ and

q is the rotation quaternion as defined above. Finally, q^{-1} is the conjugate quaternion (described in Equation 2). Quaternion multiplication is a noncommutative operation described in other sources.[7]

$$q^{-1} = < -x, -y, -z, w > \tag{2}$$

$$p' = qpq^{-1} \tag{3}$$

Fortunately, the T265 returns its pose rotation as a unit quaternion, which is necessary for Equation 3 to preserve the magnitude of v. Another important mathematical concept in the construction of the augmented reality program is the inverse pose. Where a pose is an object containing the current translation of the camera and rotation away from its boot-up coordinates (initial pose at $t = 0$). The inverse pose has the property where when 'applied' (speaking in a functional sense) to a set of coordinates, they appear perfectly stationary in space relative to the T265 camera. The inverse pose consists of the negated translation vector, and the conjugate of the current rotation. This is the basis of how the radar data is represented using live augmented reality.

4.2 Radar Signal Processing

The Walabot returns an amplitude modulated signal. See Figure 2. The intensity of a reflection at a certain point is represented by an increase in amplitude at that point. The time axis represents the time from signal transmission to reception.

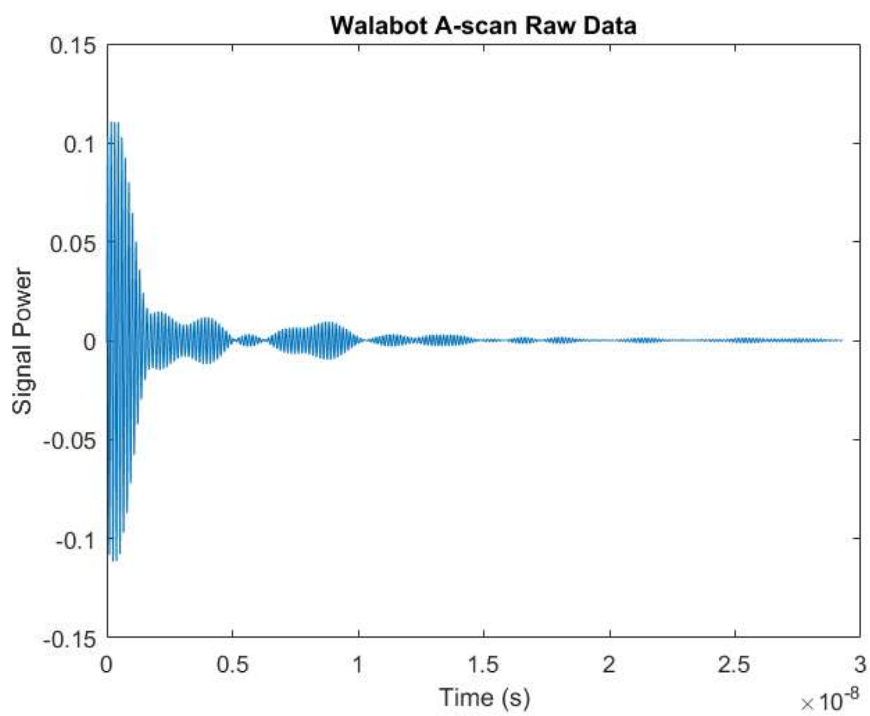


Figure 2: Raw A-scan data from the Walabot showing the amplitude modulated (AM) form of the signal

In order to extract meaningful data from the raw signal, the Hilbert transform is used in order to read the 'envelope' of the AM signal.[8] The magnitude of the complex value returned from the Hilbert transform is now the A-scan extracted from the AM signal. Figure 3 shows the envelope of the above signal. This removes the carrier frequency of the AM signal making it easier to use conventional radar algorithms to find targets.

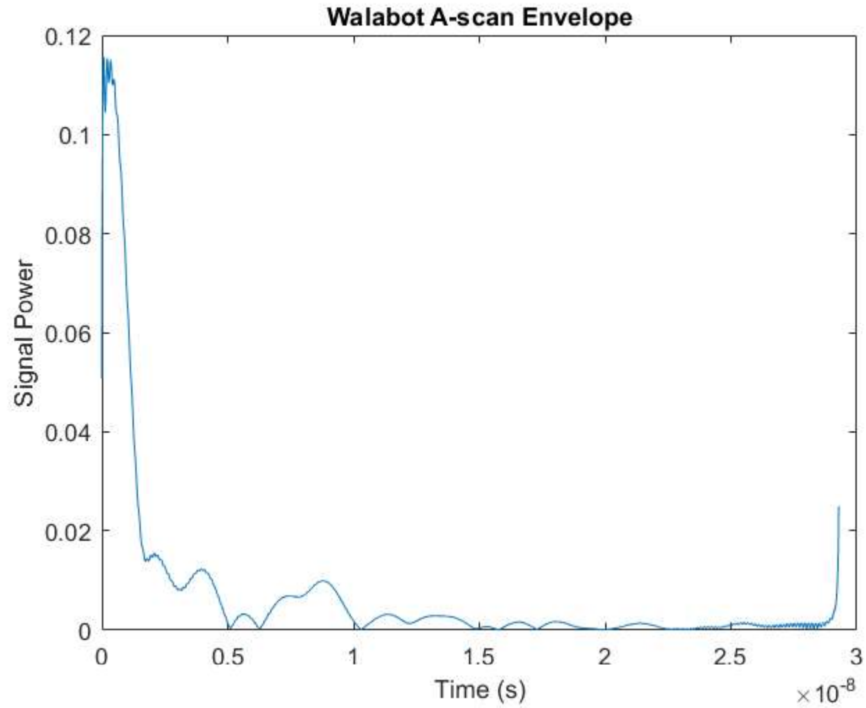
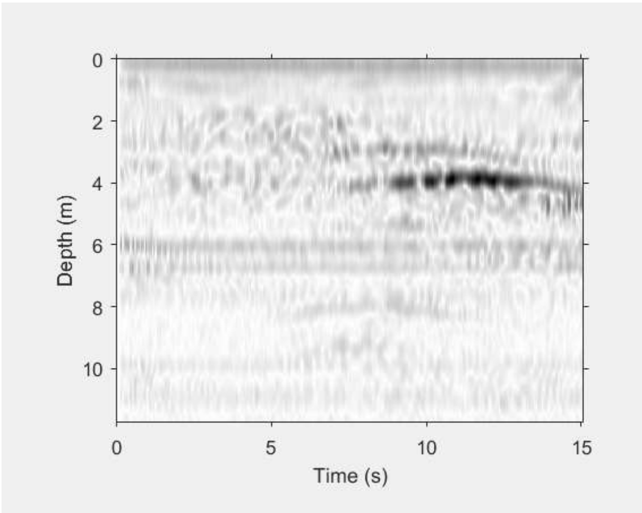


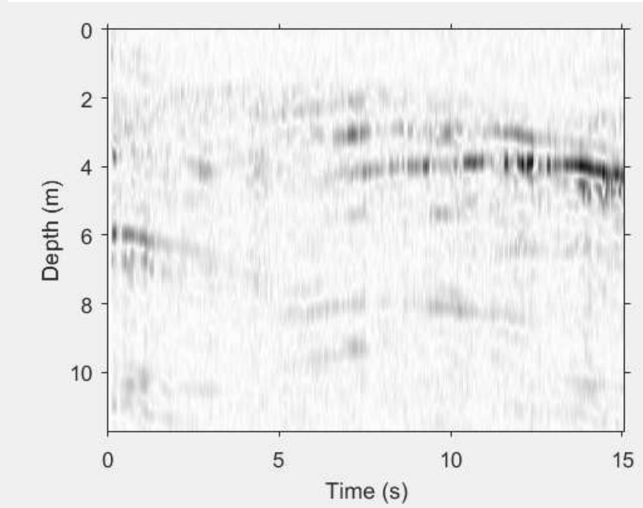
Figure 3: Envelope extracted from the signal in Figure 2 using the magnitude of the Hilbert transform

For the scope of this project, a simple background subtraction algorithm was chosen in order to negate large signal features only present due to constants in the scanning field, whether it be the casing of the radar antennae or some signal artifact. For example, the large spike near 0 in Figure 3 never varied with any target it was simply due to the construction of the Walabot, and thus background subtraction negated it.

Following in Figure 5 are two B-scans using the Walabot to ensure that the background subtraction algorithm was helping make targets more clear. This is a conventional method to view radar data and therefore it would be clear if anything out of the ordinary was taking place. The scanning field was a room with large metal appliances around and the radar was rotated at the center in order to try and get a reflection from the different targets. Metal targets are focused on throughout this paper since they are extremely strong reflectors of radar frequency EM waves.



(a) B-scan of large targets with no background subtraction



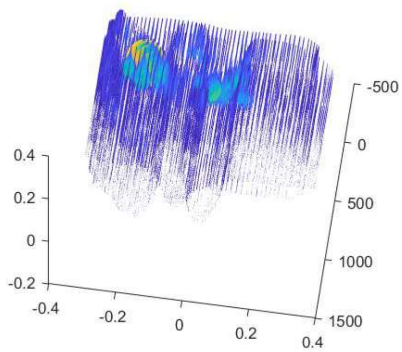
(b) B-scan of large targets with background subtraction

Figure 4: A comparison between scanning with background subtraction and without

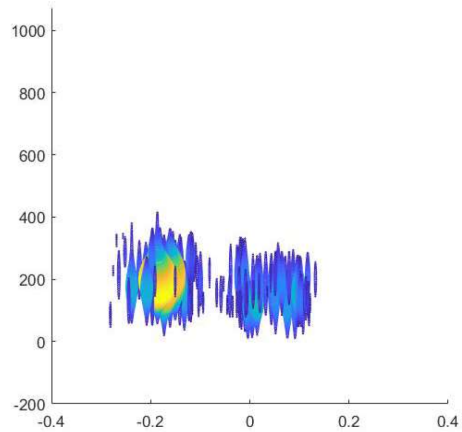
In Figure 4b it is clear that some sort of artifact due to the initial scan was 'dragged' through the full duration of the B-scan. Removing this constant through subtraction helped make the signal clearer and reveal more targets, as well as some weaker reflections.

5. RESULTS

With the combination of the methods listed above, the result was a code structure and algorithm that can be appended to any radar scanning device, when used in conjunction with the T265 tracking camera. First, some results without augmented reality will be shown. These were preliminary 3-D scans done while it was still being determined how the data will be visualized, so the data axes values are meaningless but for the sake of discussion, consider them to be spacial coordinates. The resulting data-sets that are produced are not A or B scans, but they are of a new type. They are a sort of free-form B-scan, hereby referred to as a free-scan (F-scan, for short). The subject scanned in Figures 5a - 6 was a pair of metal bowls spaced apart sitting on a flat wooden surface. This was the first experiment with F-scans and did not have the rotational component of scan orientation defined yet. The radar antenna was fixed to point straight down and waved over the targets with the camera attached to it in a purposefully haphazard manner. The resulting pointcloud is plotted in Figure 5a. The size and color of each point is dependent on the Hilbert transformed signal power at that point.



(a) F-scan of two metal bowls



(b) The same F-scan with all points under a certain threshold removed

Figure 5: A comparison between raw and filtered F-scans

The next step is to define a power threshold under which any of the data points are hidden so the targets are more clear. The filtered data is shown in Figure 5b. At this point the targets are becoming clear. To make the significance of this type of data representation more clear, the same F-scan is shown in a flat 2-D B-scan style in Figure 6. Clearly, the 2-D representation is nearly useless and it is only the localization of the data from the camera pose that helps the targets become clear.

Figure 6: The F-scan from Figures 5a and 5b laid flat on a 2-D plane in the style of a B-scan

Finally, using the live feed of the camera in conjunction with above radar methods and quaternion algebra, the augmented reality program can be run. The chosen method for representing signal power on the screen was to place a dot at any point in space where the signal breached a certain threshold, and to modulate color and size based on signal reflection intensity. The T265 and Walabot are fixed together and can be used live like a virtual paintbrush to 'fill in' the area of interest. The result of this scan is shown in Figure 7, where the devices are used to inspect a closed case.

Figure 7: A suspicious case, now with live AR radar, the user can see what is inside.

Using the modulation of data point size and color, highly reflective hot spots are visible on the screen. Furthermore if the contents of the case are not clear from one angle, the user can walk around to any vantage point and the representation in 3-D on the screen is adjusted accordingly. Figure 8 shows an overlay of the open case for reference. Finally, Figure 9 shows the case from another angle. The depth of the target can be found in this figure by noting the location of the highest reflective areas.

Figure 8: An overlay of the opened case is shown in post processing to help reveal the contents

Figure 9: Side view of the closed case, the target depth is visible due to dot size and coloration.

6. CONCLUSION

The methods presented in this paper resulted in a system that can be used to scan through walls and barriers in real-time. The user can generate 3-D models using radar data that are shown in an augmented reality environment. Applications spread from law enforcement and military (threat detection) to civil engineering and home projects (pipe or wall stud location). The main drawback to this particular setup is the weakness of the Walabot's transmission signal. It has a hard time detecting objects if they are obscured by dielectric material such as wood, more than 30cm (about a foot) away. That being said, the T265 and existing code infrastructure can be applied to any radar system. For future work it would be interesting to see this method applied to larger more powerful radar systems particularly in the ground penetrating field, or for personnel detection through barriers.

ACKNOWLEDGMENTS

This project was support in part by the U.S. National Science Foundation project no. 1647095, and the University of Vermont Spark Fund

REFERENCES

[1] Dryver Huston, Peter Fuhr, K. M. W. W., "Nondestructive testing of reinforced concrete bridges using radar imaging techniques," *The New England Transportation Consortium* , 1–177 (2002).

[2] Andrea BENEDETTO, Fabio TOSTI, L. B. C. F. D., "An overview of ground-penetrating radar signal processing techniques for road inspections," 1–26 (2016).

[3] Cote, S., "Augmented reality for subsurface utilities : further improving perception https://communities.bentley.com/other/old_site_member_blogs/bentley_employees/b/stephanecotes_blog/posts/augmented-reality-for-subsurface-utilities-further-improving-perception?CommentId=e0814cdd-6c62-416a-ba56-f96d0e22e992," *Bentley Applied Research* (2012).

[4] Imaging, V., "Walabot api." https://api.walabot.com/. (Accessed: 2 February 2020).

[5] Realsense, I., "pyrealsense2 documentation." https://intelrealsense.github.io/librealsense/python_docs/_generated/pyrealsense2.html. (Accessed: 27 August 2020).

[6] OpenCV, "pyopencv documentation." https://docs.opencv.org/master/. (Accessed: 1 December 2020).

[7] Matt Pharr, G. H., "Physically based rendering (third edition)," *Science Direct* (2017).

[8] Mathworks, "Mathworks documentation." https://www.mathworks.com/help/signal/ug/envelope-extraction-using-the-analytic-signal.html. (Accessed: 1 December 2020).