Progress Report - 8 July 2023

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1 Recap of the Problem

Radar is gaining a lot of attention recently in the context of robotic navigation as a more robust alternative to Lidar. The work here is not making use of radar images for navigation, but rather using robotic vehicles to collect high resolution below-ground imaging ones to be used for example in humanitarian demining operations. As previously discussed, the aim of my work is to explore how to apply Interferometric Synthetic Aperture Radar (InSAR) techniques, employed in space satellites, to a Ground-Penetrating Radar (GPR) system in order to obtain higher-resolution images in less time. InSAR is applying SAR on multiple vehicles equipped with radar and reconciling their data in such a way so as to obtain greater resolution [KHP+10]. SAR is applied on one vehicle, with its underlying principle being to mimic a larger aperture by moving the vehicle and tracking its position. So far, to my knowledge SAR has seldom been applied in the GPR context, and has yet to be employed on multiple vehicles [BLS+22].

Demining equipment, whether in a military or humanitarian context, usually has both GPR and metal-detecting capabilities because mines can be largely metallic, minimally metallic, or completely nonmetallic. False alarm and missed detection are serious issues out in the field as a result of these configurations. GPR, no matter what context in which it is used, generally obtains images that require trained people to interpret, as they are not, like common belief (or wishful thinking) might have it, a clear "x-ray scan" of the ground. Due to the complex and changing conditions of the ground, the images obtained vary and undergo different skewing effects that increase the difficulty to interpret even for a trained crew.

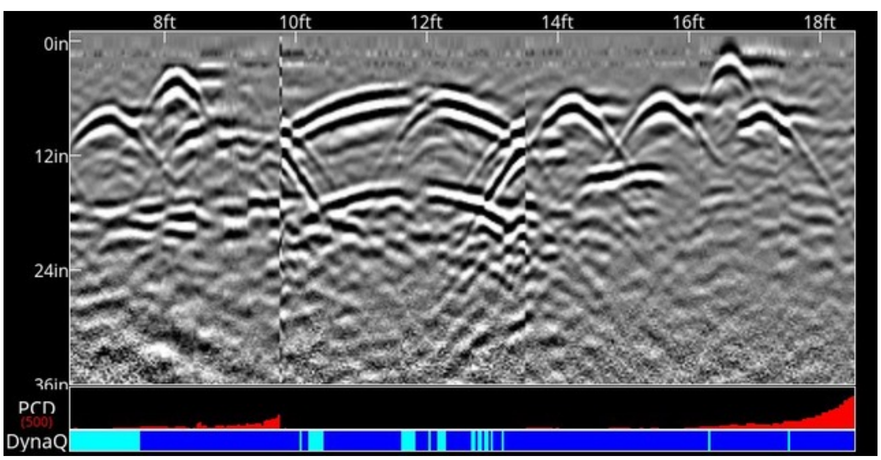

Figure 1: Typical GPR image

What I aim to address in this work is how to obtain higher resolution images (1 cm object should be discernible) of the underground at relatively shallow depths (up to 1 meter) and keeping the time it takes to perform scans low so as to be able to cover large areas of land. Humanitarian demining operations take a long time due to the challenges outlined previously.

2 Solution Exploration

Because mines are dangerous and can be set off with relatively minimal physical contact, and the terrain can be tricky to traverse on wheels or legs, flying drones are considered good vehicle platforms for GPR equipment. One solution I want to explore is equipping multiple drones with GPR, and having them move together (their relative location and motion will likely matter) while transmitting pulses and receiving reflections from the ground. Upon hitting an interface, EM waves scatter and in a mixed medium such as soil, scattering is significant and the resulting image suffers.

In general, optical systems can increase resolution by increasing aperture size, because they are thus able to capture more light. Practically, there is only so large that we can make any aperture, so *synthetically* mimicking a larger aperture is the way that resolution increases in these system. As mentioned, SAR in a GPR context has been recently applied on a drone, but it was rather slow in the field. I want to decrease the time it takes by changing/expanding the antenna configuration. I need to first understand how to apply SAR on one GPR system, and then as I learn more about antenna configurations, hopefully come up with a multi-GPR scheme that I can demonstrate works.

Throwing more antennas at the problem may seem like just increasing the aperture size as mentioned before, but it is worth considering because it is more flexible if it is on multiple moving platforms that can change relative position, and also with the idea that we can decrease the survey time and thus cover more ground.

3 Progress so far

First, I wanted to learn more about the world of radar technologies which includes their working principles and jargon. To summarize, RADAR (Radio Detection and Ranging) is a mature technology that relies on the principle of a transmitting antenna emitting EM waves and, upon hitting an object, some part of the signal returns to a receiving antenna. Measuring the time the signal takes to return, the system can estimate the distance of the object from the radar. Ground-penetrating radar is more intricate because we are trying to image what is underneath the ground, a heterogeneous medium where much signal scattering and attenuation takes place. Yet, it is essential for applications where one could not simply dig to see what's below.

Then, I learned more about what underlying simulations would be required to verify any antenna configurations I would employ. Consulting some literature, I came across the *Finite Difference Time Domain (FDTD) Method* that is the basis for how EM wave propagation is modeled on computers. The underlying principle is that Maxwell's equations are approximated by finite differences, and space is discretized into a grid with values of the electric and magnetic field and permittivity are defined in each grid box. The principal discetization method is the Yee grid, named after Dr. Kane Yee who came up with a schema that was shown to model quite well what we observe in real life while still remaining computationally feasible [Yee66]. One key component of the Yee grid is that the x, y, z components of E and M are staggered on each grid box, such that adjacent magnetic field components circulate the electric field components and vice versa.

My initial instinct was to try to write the formulations in code myself, but I realized that while the Yee grid principle is not itself difficult, there are quite a few subtleties regarding how EM waves scatter upon interacting with different media that have been met with a lot of resources and study in terms of how to best incorporate them in simulation. Therefore, I decided to use gprMax, an open-source, relatively extensive implementation of the FDTD method applied specifically with the GPR context in mind including soil modeling tools and antenna testing capabilities in order to remain as close to real life as possible, since I am not at this time able to use a real hardware testbed. [WGG16]

I started playing around with gprMax and I was able to gather more insight on the theoretical problem as well as simulation issues. Simulating even a small 1 cubic meter space with antennas requires a lot of computational resources, so I will have to think about whether 2D will be sufficient. Even if I can demonstrate that we can achieve high resolution along a 2D slice, it will still be meaningful. However, I am wondering if the possible antenna configurations are severely limited in simulation in this setting.

References

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