Chapter 8. Conclusions and future work

8.1. Conclusions

The work reported in this thesis on the use of the ultra-wide band (UWB) GPR as a possible demining sensor was made in the frame of the Belgian HUDEM project. The potential of detecting non-metallic objects makes GPR complementary to a metal detector in the application of AP landmine detection. At the moment, the use of conventional GPR in real demining operations is negligible, mainly due to three drawbacks. The first drawback concerns the antennas used in commercially available GPR systems. In most cases, GPR antennas have a low directivity and therefore perform best when they are in contact with the ground, in order to couple as much energy as possible into the ground. For safety reasons, deminers do not want to use a sensor that is in direct contact with the ground. The second drawback is the limited depth resolution of conventional GPR systems. The range resolution (in this case depth resolution) of a GPR is, just as in any other radar system, directly related to its bandwidth. As anti personnel landmines are often shallowly laid, conventional GPR can have difficulties in discriminating the target echoes from the air-ground interface, especially when the surface is rough. In this case, more depth resolution is needed, which means a larger bandwidth of the system. A third problem with the conventional GPR systems is the inability of discriminating between a mine and a mine-like target. This problem, also related to the frequencies used by the GPR system, has to be solved by using appropriate signal processing. To investigate the feasibility of possible solutions for all of these drawbacks, we have built a relatively simple UWB

GPR systems, using mainly off-the-shelf equipment. The system uses frequencies between 1 and 5 GHz, with a central frequency of 3 GHz. The upper cut-off frequency seems to be a good compromise between the resolution of the system and the attenuation of the higher frequencies in the ground. In accordance with the philosophy of the HUDEM project, the intention of this work is not to produce a ready-to-use mine detector. The work consists in a contribution to UWB GPR in order to help industrial designers in the development of this kind of sensor for mine detection.

In agreement with the above mentioned problems, three main personal contributions have been made in association with this work:

1. the development and testing of small UWB GPR antennas, which can be used off-ground,
2. the modelling of the UWB GPR system in time domain, and
3. the development of a novel migration algorithm, using the time domain model of the system.

As one can see, this work is not limited to only hardware or software aspects of the UWB GPR, but a more overall system approach is followed, starting from the development of some critical hardware parts, over system modelling towards signal processing, integrating the knowledge of the system in the processing part. The latter is probably one of the most original parts of the work.

8.1.1. UWB antennas

The demining application imposes specific requirements to the GPR antennas, the most important of which being the mobility of the antennas and the bandwidth. As minefields have often a very rough surface and can be covered with a lot of vegetation, the antennas have to be mobile. This means that they have to be small, light-weighted and directive, so that they can be used off-ground. The TEM horn seemed to be a good candidate to meet these design goals. In a first step an air-filled TEM horn was studied and developed. It is shown that the wire model is an accurate model for the design of such an antenna. The wire model is not too complicated to implement and it permits to simulate accurately the peak-to-peak antenna pattern as well as the surge impedance. In order to reduce the physical size of the antenna and to improve the directivity, the antenna was filled with a dielectric. Due to the lack of a good model, the design was based on the air-filled antenna, assuming that the antenna guides a quasi-TEM wave. Time domain reflectometry measurements of the surge impedance showed a slight but acceptable difference with the theory. Antenna measurements revealed that the dielectric-filled antenna is indeed more directive compared to an air-filled antenna of the same dimensions and that the frequency range moved towards the lower frequencies. The antenna plates were replaced by a set of wires, which makes them suitable for operating in combination with a metal detector. An ultra-wideband balun was also integrated in the antenna plates. The dielectric-filled TEM horns are capable of radiating and receiving very fast transient pulses, without too much ringing, which is of course important for this application. The cleaner the pulse, the cleaner the backscattered signal, and the more easy it will be to post-process and interpret the data.

8.1.2. Time domain modelling of the GPR

A second main contribution was made in the domain of system modelling. Normally, the performances of radar systems are characterised in the frequency domain. In this work we described the whole system, *i.e.* GPR system, ground and target, in the time domain by considering it as a cascade of linear responses, resulting in a *time domain GPR range equation*. The time domain GPR range equation allows us to calculate the received voltage as a function of time at the receiver in terms of the radar, ground and target characteristics. The time domain model is used to optimise the offset angle for the GPR antennas. The study revealed that the optimal offset angle for the antennas is the one that focuses the antennas on the target. Furthermore, the range performance of the UWB GPR system is calculated by the time domain GPR range equation, for a given target in a given soil. It was shown that the moisture content of the soil limits drastically the range performance of the UWB system.

A key element in the modelling of the radar is the description of the antennas in the time domain by means of the normalised IR. This explains why a whole chapter was dedicated to this topic. In that chapter we showed how the normalised IR describes in a compact way the time domain antenna characteristics, which are sometimes difficult to see in classical antenna parameters. The success of the normalised IR is that it includes all frequency dependent characteristics. This gives two important advantages. First, the time-domain antenna equations become very simple and accurate. Second, the normalised IR permits a comparison between different variants of time domain antennas. Due to the finite but non-zero size of the antenna, the distance from an observation point to the antenna becomes ambiguous for points close to the antenna. Therefore we introduced an apparent point in the antenna, called the virtual source, which can be seen as the origin of the radiated impulse TEM wave. The knowledge of the position of the virtual source is important when the antenna equations are used near the antennas or for the measurement of the normalised IR of the antennas. The normalised IR on boresight is easy to measure, using two identical antennas and a vector network analyser. We also showed that, within the 3dB opening angle of the antenna, the normalised IR off-boresight can be derived from the normalised IR on boresight, using the p-t-p antenna pattern. This means that within the 3dB opening angle an antenna is totally characterised in the time domain by its normalised IR on boresight and its p-t-p pattern.

Another important term in the time domain radar range equation, besides the IR of the antennas, is the IR of the lossy ground. In this work we proposed an analytical expression of the impulse response, modelling the propagation in the ground. The expression of the impulse response is calculated from the theoretical frequency response function of the lossy ground and takes into account the attenuation and the dispersive behaviour of the ground.

The targets in the ground are also characterised by an IR. In general we can say that the dimensions of the targets are of the same order of magnitude as the wavelengths in the ground used by the GPR. This means that we are primarily working in the resonance region of the scattering, leading to scattering centres that appear later in time than the reflection on the back of the target.

As a whole, the time domain modelling was found to be a powerful and accurate tool for describing and studying a time domain system and this type of modelling is recommended to all those who work with time domain systems.

8.1.3. Migration

A last main contribution was made in the domain of the 3D signal processing. Most of the existing migration techniques do not take into account the characteristics of the acquisition system and the ground characteristics. As we dispose of a good time domain description of our UWB GPR, we proposed a novel migration method that integrates the time domain model of the UWB GPR in the migration scheme. We calculate by forward modelling a synthetic 3D point spread function of the UWB GPR, *i.e.* a synthetic C-scan of a small point scatterer. This 3D point spread function, containing system characteristics like the waveform of the excitation source, the combined antenna footprint and the IR of the antennas, is then used to deconvolve the recorded data. Results of this migration method on real data obtained by the UWB GPR system show that the migration method is able to reconstruct the top contour of small targets like AP mines, in some cases even with the correct dimensions. The method is also capable of migrating oblique targets into their true position. The migration scheme is not computational intensive and can easily be implemented in real time.

8.2. Conclusions on the use of a UWB GPR as a mine detector

From the experience we have obtained by working with the UWB GPR for mine detection, we learned that the difficulty of detecting small objects in an inhomogeneous background is often underestimated. One should not forget that, in contradiction to many other imaging techniques, the number of measuring points with a GPR is limited. One can only measure by moving the antennas in a half-space above the target. Furthermore, the subsurface that is to be imaged can contain a lot of clutter and the air-ground interface can be very rough, which makes the interpretation of the images difficult. Therefore, the UWB GPR will most likely **never be used as a stand-alone mine detector**, but always in combination with other sensors.

In this research the advantages as well as the shortcomings of the UWB GPR as a mine detector are addressed. As a summary we can say that, as expected, the UWB GPR is capable of detecting shallow buried mines and even mines that are laid on the surface. The tests also confirmed that when mines are buried deeper and the soil has a high moisture content, the detection becomes almost impossible. This means that in practice the UWB GPR can only be used as **a detector for shallow buried objects**. Despite the large bandwidth of the system, signal-processing techniques on A-scans have limited success. None of these methods seems to be robust enough to be used for classification purposes. The by the author **recommended way of using the UWB GPR is to record C-scans**. After migration, the buried objects are replaced into their true positions and the 3D images have enough resolution for extracting the shape of the object. If not too much noise and clutter is present in the recorded data, it is even possible to retrieve the exact dimensions of the buried object. This additional information on location, shape and dimensions of the target will drastically reduce the number of false alarms and thereby speed up the mine clearance.

8.3. Future work

The way towards a reliable, robust, cheap and field usable hand-held version of an UWB GPR is long and there is still a lot of research and development to do. In this respect the topics of possible future work are inexhaustible. In this section we limit us to some topics with are considered by the author as not fully finished in his work or in a logic continuation of his work.

A first topic of future work resides in the field of antennas. Although the TEM horn antennas that are developed in the scope of this work meet almost all of the design goals, it is still possible to enhance the TEM horn antennas (*e.g.* resistive loading in combination with the dielectric filling) or to explore other types of antennas. A promising candidate, which currently gains in interest for the stepped frequency ground penetrating radar, is the Vivaldi antenna. The Vivaldi antenna is light-weighted and small, has a very large bandwidth and can also be used off-ground. The question here is how the antennas will perform in a time domain system. Other interesting types of antennas are antennas with circular polarisation. These antennas would permit full-polarised measurements without additional effort and loss of time in the measurement process. Another challenge is the integration of GPR antennas in the search coil of a metal detector (MD). The integration contains two difficulties. First, the metal in the antenna plates may not disturb the good functioning of the MD, but more difficult, the search coil of the MD may not introduce additional ringing in the GPR measurements.

A second interesting research topic lies in the domain of signal processing. For the moment the migration by deconvolution uses the Wiener filter to deconvolve the point spread function from the recorded data. The Wiener filter is an optimum filter under certain assumptions, which are not necessarily fulfilled in our case. Further there is in this method the problem of estimating the spectral densities of the noise and the original image. It is possible that there exist better techniques to perform the deconvolution in the migration scheme.

Related to the signal processing is the presentation of the processed 3D data. Until now only a few researchers have concentrated on this topic, but a clear and simple man-machine interface is difficult to build and a lot of work can still be done in this domain.

The last topic we propose is only relevant in case the UWB GPR should be integrated in a hand-held system. In Section 8.2 we recommend to record C-scans, which will then be processed before showing to a human operator for interpretation. For the processing of the data, it is necessary that the exact position of each recorded A-scan is known. This means there is a need for a precise, light-weighted and cheap positioning system that has to be integrated with the UWB GPR and the other sensors. The positioning system must not only provide the exact position of the search head, but also its orientation.