Determining of the subsurface object coordinates using 1Tx + 4Rx antenna system at incomplete set of reflections

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***Abstract*—The impulse GPR with 1 transmitter and 4 receivers (1Tx+4Rx) antenna system is an important part of team of robots responsible for plastic mines detection. It is critical to provide reliability of its work even if only parts of 4 Rx antennas receive reflection from mine. The paper considers the possibility of improving the probability of detecting objects and determining its coordinates using UWB radar with 1Tx+4Rx antenna system in case if only two Rx antennas are able to register reflection from the mine.**

Keywords — ultrawide band (UWB) impulse, ground penetrating radar (GPR), subsurface object detection, time of flight (TOF), data processing.

I. INTRODUCTION

One of the most dramatic outcomes of the war in Ukraine is the contamination of a vast territory with a different kind of mine. Recently State Emergency Service of Ukraine (SESU) issued an interactive map of areas that could potentially be contaminated by explosive objects [1]. This map shows the places where explosive objects have already been found or are likely to be found and the degree of threat from them according to the information available at the SESU (localization error is up to 30 m).

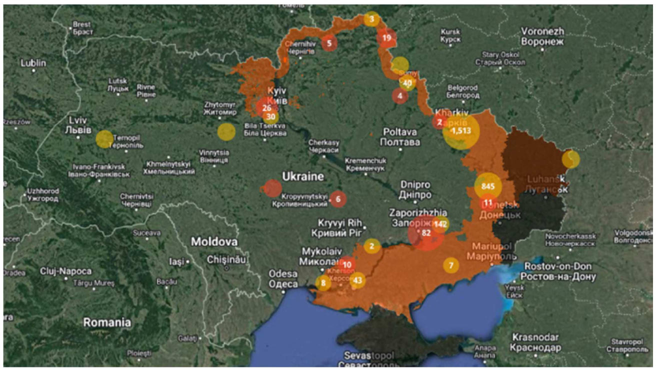

Fig. 1. Interactive map of areas that could potentially be contaminated by explosive objects

Currently, humanitarian demining is needed in an area of about 270,000 square kilometers in Ukraine [2].

The authors of the paper developed a multisensor robotic platform for landmine detection. The NATO Science for Peace and Security (SPS) Project #G5014- "Holographic and Impulse Subsurface Radar for Landmine and IED Detection" [3] was devoted to this task. To achieve real-time detection and determine coordinates of subsurface objects by the impulse GPR with a specially designed 1Tx+4Rx antenna system, we developed the algorithm based on the use times of flight (TOFs) of probing signal from the transmitter to the object and back to each of 4 receivers [4].

In the beginning, the proposed algorithm required getting all four TOFs detected by all four receiving antennas. However, for different reasons, some receivers could miss reflection. It could happen for different reasons: from clutter conditioned by radio systems working close to the GPR to when the reflection coefficient from the object is so tiny that the reflected signal is undetectable. In this case, determining of coordinates of the subsurface object is impossible. To overcome this problem, we proposed an algorithm that requires only 3 TOFs [5]. Any combination of these TOFs allows the calculation of the subsurface object coordinates.

Although we provided additional steps to increase the reliability of the Impulse GPR detection system, at the radar probing, it is possible receiving of only two signals. In this case, both initial and advanced algorithms can not calculate subsurface object coordinates, leading to missing detection.

Our next advance provides the possibility to detect the subsurface object and calculate its coordinates based only on two TOFs. It is evident that we need a minimum of three measurement results to calculate three coordinates. Two TOFs are insufficient. However, it is valid for static. During probing, the GPR moves along a certain path (line). Due to movement, we can get a third measurement necessary for the determination of the coordinates.

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In this paper we describe how to determine the coordinates of the subsurface object using only two TOFs and the movement of the GPR.

II. METHODOLOGY DESCRIPTION

The geometry of the problem is shown in Figure 2. The transmitter Tx is located in the center of the rectangular coordinate system XYZ. Four receivers Rx1, Rx2, Rx3, and Rx4 are distributed on the OX and OY axes on either side from transmitter Tx at a distance of l/2. Object M is located under XOY plane.

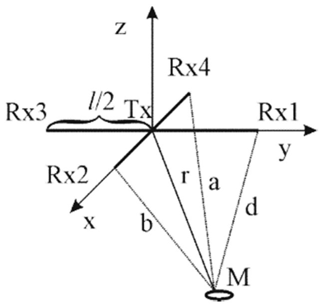


Fig. 2. The geometry of the problem in 3D space

Let us only two opposite receivers Rx2 and Rx4 are able to receive signals reflected by the object M. Let us denote the TOFs of the probing pulse from the transmitter Tx to the object M, and then to each of the receiving elements Rx2 and Rx4 as t_2 and t_4. Then path lengths from Tx to the object M and then to the Rx2 and Rx4 are $T2 = t_2 v$ and $T4 = t_4 v$ correspondently. Here v is the velocity of pulse propagation.

So, we have:

$$T2 = r + b \qquad (1)$$

$$T4 = r + a \qquad (2)$$

At first we calculate a distance r from the origin of reference system to the object M. Consider the plane R2x-M-Rx4, determined by three points: positions of the receiving antennas Rx2 and Rx4 and position of the object M (Fig. 3). The geometry of the problem in the plane Rx2-M-Rx4 is shown in Fig. 3.

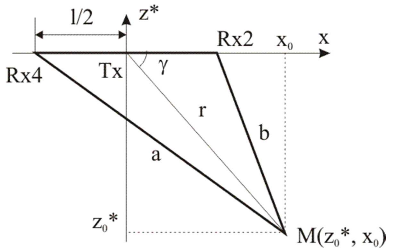


Fig. 3. The geometry of the problem in the plane Rx2-M-Rx4.

From the triangles M - Tx - Rx2 and M - Tx - Rx4 using the *cosine* theorem we can write:

$$b^2 = r^2 + \left(\frac{l}{2}\right)^2 - rlcos(\gamma) \qquad (3)$$

$$a^2 = r^2 + \left(\frac{l}{2}\right)^2 + rlcos(\gamma) \qquad (4)$$

If we combine expressions (1 - 2) and (3 - 4), we can get two expressions for elements with cosine:

$$rlcos(\gamma) = T2(2r - T2) + \left(\frac{l}{2}\right)^2 \qquad (5)$$

$$rlcos(\gamma) = -T4(2r - T4) - \left(\frac{l}{2}\right)^2 \qquad (6)$$

Then we equate the right sides of the (5) and (6) and get the distance r from the origin of reference system to the object M:

$$r = \frac{(T2)^2 + (T4)^2 - 2\left(\frac{l}{2}\right)^2}{2(T2 + T4)}. \qquad (7)$$

Coordinate *x* of the object M we obtain using the triangle Tx-M-x_0 (Fig. 3) and expression (5):

$$x = rcos(\gamma) = \frac{\left[T2(2r - T2) + \left(\frac{l}{2}\right)^2\right]}{l}. \qquad (8)$$

Thus, we have a problem of defining *y* coordinates of the object. We have no extra TOF for calculation. However, we can use such a property of B-scan as corresponding of position of vertices of hyperbola to configuration when the distance between the object and Tx and Rx antennas is minimal. It happens if the most reflecting point of the object surface is located in the XZ plane. Namely, when in the coordinate system connected to the antenna $y = 0$. (The GPR moves along the *y* axis.)

At that, we obtain the position of the object directly according to the position of the hyperbola vertices in the B-scan.

Now we know the coordinates *x* and *y* of the object M in the 3D spatial coordinate system. This allows us to find the z-coordinate of the object M, which is the distance from the antenna plane to the object. As far as $y=0$, then

$$z^2 = r^2 - x^2 \qquad (9)$$

Since the object is located below the plane of the antenna system, the sign of the *z*-coordinate is negative.

III. EXPERIMENTAL RESULTS

The experimental part of the research was done in the test field in the garden of the University of Florence, where we buried objects for future study (Fig.4).

Fig. 4. For example, PMN4 (on the left) is burried (on the right).

Three types of objects: metal tin, PMN4, and a simulant of PMN 1 were buried for these experiments (Fig.5). All these objects stayed in the ground for three months as a minimum. During experiments, we collected an extensive set of GPR data, which is helpful for indoor analysis.

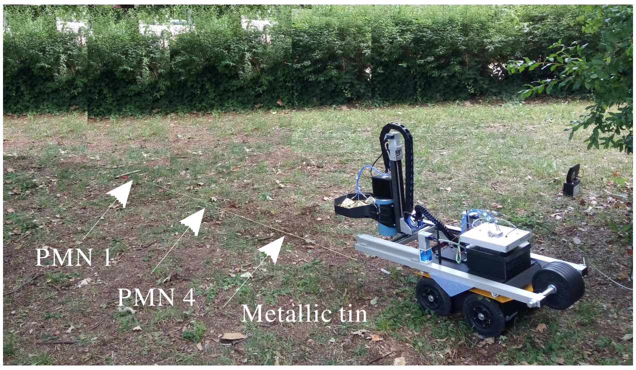
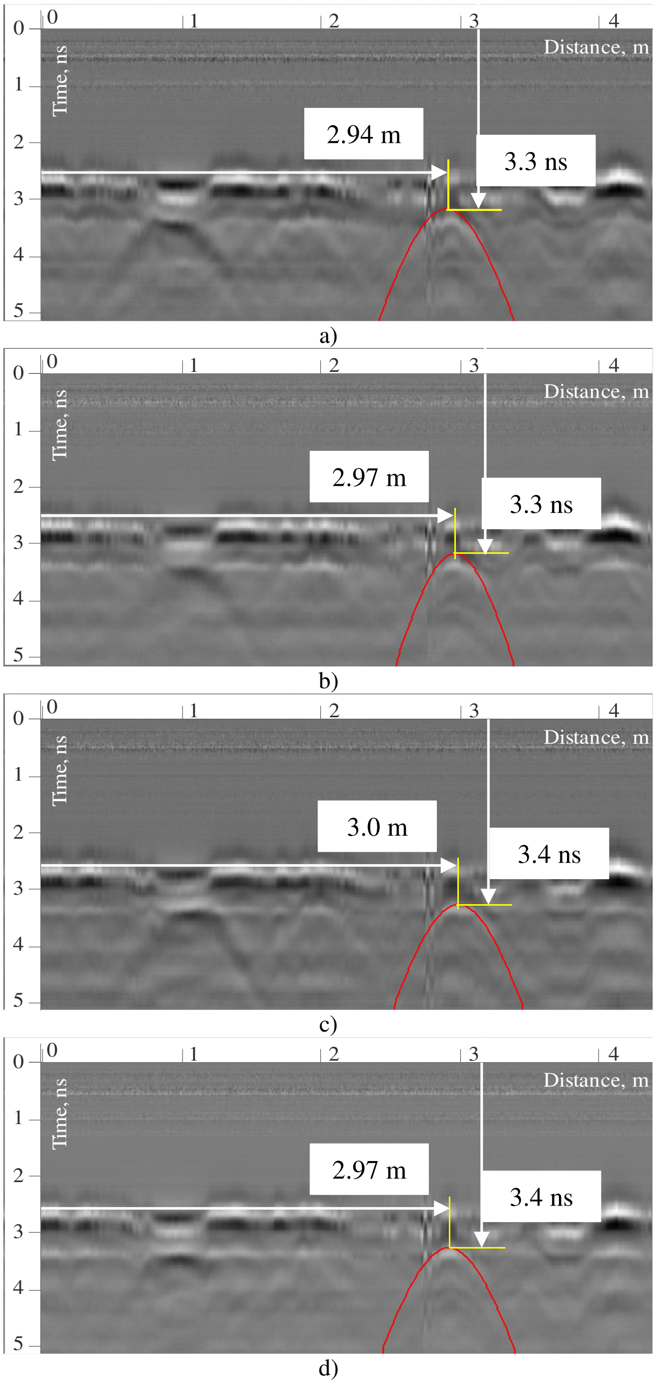


Fig. 5. Test line. Three objects are burried in the soil: metallic tin of diameter 12 cm, simulants of mines PMN4 and PMN1.



a)

b)

c)

d)

Fig. 6. B-scans in 4 channels. *y* coordinates and TOFs for the PMN 1 are shown for vertices of hyperbolas.

Fig.6 demonstrates B-scans of the GPR data collected by four channels, Rx1, Rx2, Rx3, and Rx4, of the antenna system. Markers and figures illustrate the positions of hyperbolas vertices in the horizontal direction (along the test line) and vertical direction (in terms of TOFs). Zero of coordinates along the test line corresponds to the point of start of the robotic platform movement (left margin of the B-scan). Zero of the time scale is the top margin of the B-scan. White arrows show the directions of the scales.

It should be noted that in contrast to project G5014 [3], where real-time detection of the subsurface object was crucial because the next step of the mine detection process was determining of type of the subsurface object with a holographic radar located on the same platform, in the case of the project G5731 [6, 7] the post-processing of the impulse GPR data is allowed. It means that along with a real-time detection, the use of B-scans is possible too.

To be shorter, we choose determining coordinates only for PMN 1. Other objects' positioning is similar.

So, the step by step algorithm is as follow:

- based on the acquired data, we obtain B-scans for all channels (Fig.6);
- using an appropriate method, we draw hyperbolas corresponding to the same object in each of the B-scans;
- we find the positions of the hyperbola vertices along the test line;
- we find the TOFs based on the positions of the hyperbola vertices using a time scale.

Let's choose B-scans for the Rx2 and Rx4 (Fig.6 (b) and (d)). The Rx2 and Rx4 antennas are located on the *x-axis*, which is perpendicular to the direction of movement of the robotic platform. Naturally, coordinates 2.97 m are the same for Rx2 and Rx4 channels. Therefore the position of hyperbola vertices 2.97 m, the *y* coordinate of the object in the local coordinate system connected to the antenna system (Fig.2) equals 0. And coordinate of the object along the test line 2.97 m is a result.

The coordinates of the object on the time scale, which are 3.3 ns (for the Rx2) and 3.4 ns (for the Rx4), indicate that the subsurface object is located in the position a little bit closer to the Rx2.

In order to calculate coordinates *x* and *z,* we need to use expressions (7), (8), and (9). However, at the GPR data recording, we set the zero of the time scale so that the whole direct coupling signal was visible (Fig.7).

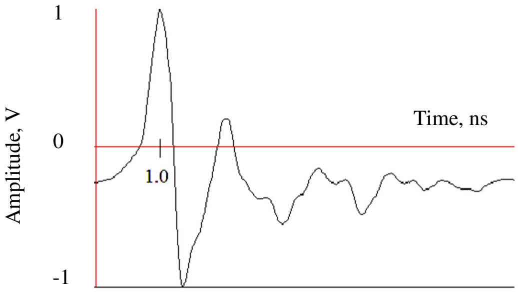


Fig. 7. A-scan in the Rx1 channel at the starting point of the data set.

Therefore for the calculation, we should use corrected TOFs: T2 = 2.4 ns and T4 = 2.5 ns. The distance between the Rx2 and Rx4 is 20 cm.

At that, r = 36.1 cm, coordinates x = 5.6 cm, and z = 35.6 cm. As it was considered, y = 0 cm and the coordinates along the test line are 2.97 cm.

For automation of GPR data processing using the proposed approach, it is necessary to apply algorithms for the automatic detection of hyperbolas vertices. Fortunately, this task is very common for GPR community, and no necessity for deep considering it in the framework of this paper. Therefore, there are only some notes..

Up to now there were developed many algorithms allowed finding coordinates of vertices of hyperbolas at the B-scans acquired by GPR from different kinds of migration [8] to automatic detection of hyperbolas with Hough transform [9] and even to use the recently very popular artificial intelligence [10, 11]. Any of these approaches is suitable for the analysis in the paper task.

IV. CONCLUSIONS

Thus, this paper continues a line of papers investigating the possibility of increasing the probability of detection of the subsurface object using the impulse GPR with a 1Tx+4Rx antenna system. Our analyses are directed to find a solution for the detection task if some receiving channels do not register reflected by the subsurface object signal because of from clutter from radio systems working close to the GPR, small contrast of the object in ground or orientation of the object leading to tiny reflection to some of Rx channels making the object undetectable.

Advantages of this approach are the absence of the strict requirement for data processing in real time (we can do data elaboration after scanning each path of the Greek line or even after finishing scanning the whole area) or the ability to use a whole set of data collected during acquisition for the analysis (it allows filtering, averaging and other means for suppression of noise).

The disadvantage of the proposed approach consists of the impossibility of detecting an object in real-time at GPR movement until coordinates of the hyperbola vertices are obtained.

It should be noted that the suggested in this paper approach does not exclude already developed methods but complements them.

We described how to obtain coordinates of the subsurface object and illustrated it using an example of the GPR data set acquired during experiments on the GPR application.

Obtained coordinates are quite good for the solution of the next step of the project [7], which is the recognition of the type of object with holographic radar.

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