

LOCATION ESTIMATION USING A BROADBAND ELECTROMAGNETIC INDUCTION ARRAY

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ABSTRACT

A broadband quadrupole electromagnetic induction (EMI) array with one transmitter and three receiver coils is built for detecting buried metallic targets. In this paper, it is shown that the locations of multiple metallic targets including their depth and cross-range position can be estimated accurately with the EMI array using an orthogonal matching pursuit (OMP) approach. Conventional OMP approaches use measurement dictionaries generated for each possible target space point which results in huge dictionaries for the 3D location problem. This paper exploits the inherent shifting properties of the scanning system to reduce the size of the dictionary used in OMP and to lower the computation cost for possibly a real-time EMI location estimation system. The method is tested on both simulated and experimental data collected over metal spheres at different depths and accurate location estimates were obtained. This method allows EMI to be used as a pre-screener and results in valuable location estimates that could be used by a multi-modal GPR or other sensor for enhanced operation.

Keywords: Electromagnetic Induction Sensor, Depth Estimation, Orthogonal Matching Pursuit, Location Estimation

1. INTRODUCTION

Electromagnetic Induction (EMI) is a very popular method used to detect the presence of metallic content in subsurface targets. EMI sensors work by affecting a region of interest with a time varying magnetic field and detecting the induced magnetic field generated by the eddy currents on the metallic target [1]. Much research has been performed on using EMI to detect buried targets such as landmines, UXO, etc.; however, much less work has been performed on making accurate estimates for the location of the target. The depth and cross-range location of the target is of particular interest here, because the down-track location of the targets are fairly apparent in the raw data from the sensor. Difficulties arise in making the location estimates, because of the nature of the EMI response. First, the EMI response doesn't measure a quantity like time delay in a radar which is directly proportional to distance. Second, the relationship between the strength and object distance is nonlinear and depends heavily on the objects size and metal content. A deep high-metal target could generate a stronger field strength than a shallow low-metal target. In [2], a polynomial curve is fitted to vertical gradient data and a classification scheme as "shallow" or "deep" is followed rather than a depth estimate. The results are rough and show a depth resolution of ± 8 inches which is not sufficient for most applications such as landmine detection. In [3], it is observed that the more distant signals have relatively stronger low frequency components and shallow targets provide stronger high frequency signals. However, no method to estimate the depth was presented.

In this paper, we propose a new method for location estimation of metallic targets in both depth and cross range using EMI data. Our technique uses the relative strength of the measured response at the receive coils of the EMI array along with the shape of the down-track response from the receive coils to make a location estimate. To use this information, the target space is discretized to generate a list of possible target positions and a model EMI response is generated for each target position to form an overcomplete dictionary of responses. Many methods have been developed to extract an optimal representation of received signal in terms of the given

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dictionary elements and this kind of search is generally called Basis Pursuit [4]. We use a type of basis pursuit algorithm, called orthogonal matching pursuit (OMP) [5], to extract the location information. Conventional OMP approaches use measurement dictionaries generated for each possible target space point which results in huge dictionary sizes for 3D location estimates. This paper exploits the inherent shifting property of the scanning system to reduce the size of the dictionary used in OMP and thereby reduces the computation cost which is necessary for a real-time EMI location estimation system.

Section 2 describes the EMI model data calculation, the dictionary generation process and the location estimation algorithm. In Section 3 experimental results with performance analysis are provided. Conclusions and future work are discussed in Section 4.

2. THEORY

2.1. EMI Model Data

In the EMI model, a transmitter generates a magnetic field, represented with a vector \mathbf{h}_T , at the target position as shown in Fig. 1. Here \mathbf{h}_T is a 3×1 vector containing the x , y and z components of the magnetic field generated by the transmitter coil, and \mathbf{h}_R is the receiver magnetic field vector at the target position when the receiver coil is used as a transmitter. These fields are calculated using the Bio-Savart law by dividing the coils into short line segments. The target is treated as a point target that can be modeled by the magnetic polarizability tensor, \mathbf{M} . It can be shown by using reciprocity that the received voltage due to the target is

$$V_{Rec} = \frac{j\omega\mu}{I_R} \mathbf{h}_R^T \mathbf{M} \mathbf{h}_T \quad (1)$$

Here \mathbf{M} can be viewed as a 3×3 symmetric matrix that represents the magnetic polarizability tensor of the target. For a metallic sphere, the tensor is diagonal $\mathbf{M} = M_0 \mathbf{I}$. The response measured by the EMI detector is

$$R = \frac{V_{Rec}}{V_{Ref}} = \frac{\mu}{L_{Ref} I_T I_R} \mathbf{h}_R^T \mathbf{M} \mathbf{h}_T \quad (2)$$

where the response is referenced to the voltage

$$V_{Ref} = j\omega L_{Ref} I_T. \quad (3)$$

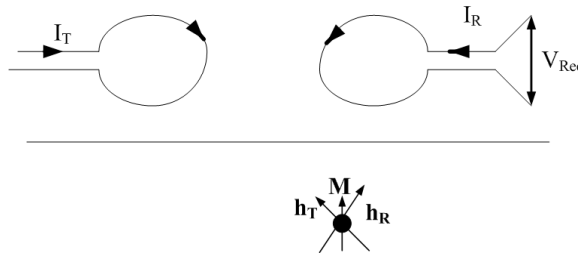


Figure 1. EMI scenario. \mathbf{h}_T is the magnetic field vector generated by transmitter. \mathbf{M} is the magnetic polarizability of the target. \mathbf{h}_R is the magnetic field vector if the receiver was used as the transmitter. V_{Rec} is the voltage measured at the receiver.

This EMI sensor measures the response at 21 logarithmically spaced frequencies from 330 Hz to 90.03 kHz for all the receive coils and records them every 0.1 s [6]. However, this work will only use the peak value of the imaginary part of the response because the method is based on relative amplitudes

Assume the quadrapole EMI array shown in Fig. 2 is scanned in the y direction to search the subsurface for targets. The response (2) for the three receivers is graphed in Fig. 3 as a function of the scan position with depth as a parameter for a target at $(x, y) = (0.17, 0)$ m buried at depths from 2 to 30 cm in 1 cm increments.

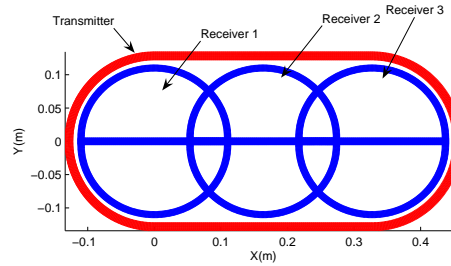


Figure 2. Quadrupole Array used for target localization.

The shape of the response as a function of scan position change noticeably as the target depth increases, and the relative amplitudes for the response of the receivers also change as a function of the target depth. The changes are more pronounced for shallow targets; less pronounced for deeper ones. Our proposed method collects all of these models into a dictionary of EMI responses for each possible target space point.

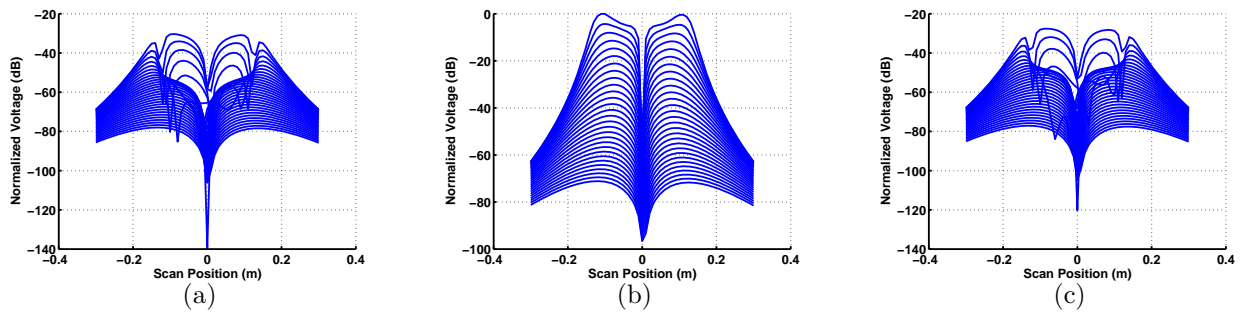


Figure 3. Normalized response for targets from 2 cm to 30 cm deep using the quadrupole array for (a) Receiver 1, (b) Receiver 2, (c) Receiver 3.

The other important location estimation parameter is the cross range, i.e., the x position of the target. The response is graphed as a function of scan position with the cross range as a parameter in Fig. 4. The target is at $y = 0$ and $z = -6$ cm with a cross range that varies from $x = 0$ to 34 cm with 2 cm increments as the array is scanned from $y = -30$ to $y = 30$ cm with 1 cm increments. The information of relative amplitude between the receivers as well as the shape of the response plays a very important role in estimating the cross range of the targets accurately.

2.2. Creating Dictionary of EMI Responses

To create a dictionary, Ψ , of EMI responses the target space π_T which lies in the product space $[x_i, x_f] \times [y_i, y_f] \times [z_i, z_f]$ must be discretized to create a finite set of possible target space points. Here (x_i, y_i, z_i) and (x_f, y_f, z_f) denote the initial and final positions of the target space along each axis. Hence, for any target position and at any scan location the received voltage can be calculated by (2) by setting $\alpha = 1$ and $\mathbf{M} = \mathbf{I}$ (assuming spherical targets). The dimensions of the dictionary Ψ will be $L \times N$ where L is the number of scan points in the scan direction. While working with such a matrix is manageable with scanning for a 2D slice of target space, for 3D target localization the number of target space points increases drastically depending on the resolution required, making it unrealistic to work with the dictionary Ψ . For example, localizing targets in an $1 \times 1 \times 1$ m³ area with 1 cm resolution would require a dictionary size of $L \times 10^6$. However, with a regular scanning pattern we can exploit a shift-invariance property of the scanning to decrease the size of the dictionary.

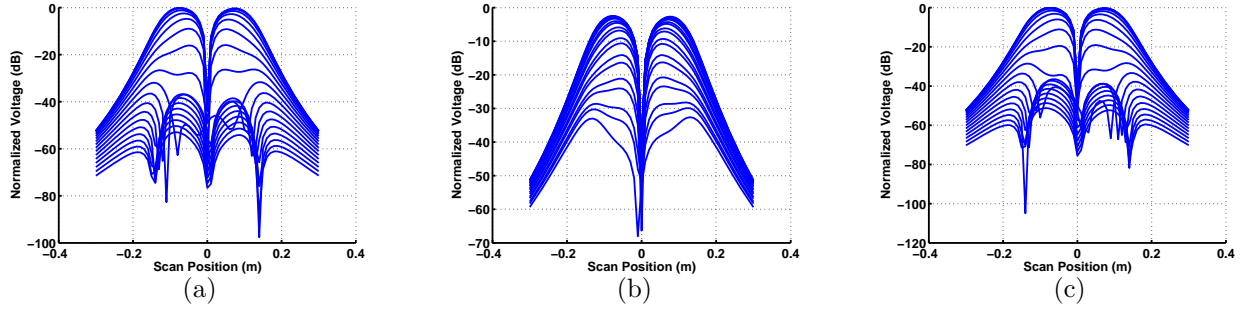


Figure 4. Normalized voltage values recorded at the receiver coils for targets at $y = 0$, $z = -6$ cm but varying in cross range with $x = 0$ to $x = 34$ cm using the quadrapole array for (a) Receiver 1, (b) Receiver 2, (c) Receiver 3.

Figure 5 shows a three-receiver, one-transmitter quadrapole array scanning along the y direction. As the array scans targets having shifted y locations but the same cross-range (x) and depth (z) values, the resulting responses in the receiver coils are shifted versions of each other. Hence it is sufficient to create a dictionary for the $y = 0$ cross range slice, and then use it to locate targets in 3D.

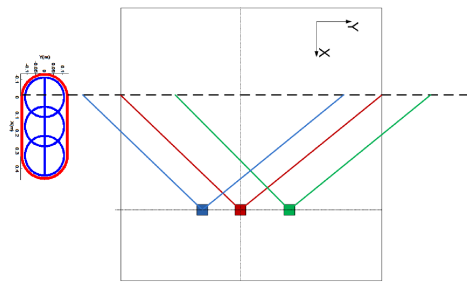


Figure 5. Quadrupole array scanning on y direction. Targets having the same x and z values create responses that are shifted versions of each other

So only the target space slice $[x_i, x_f] \times [z_i, z_f]$ is used to create the dictionary Ψ . Discretization generates a finite set of target points $\mathcal{B} = \{\pi_1, \pi_2, \dots, \pi_N\}$, where N determines the resolution and each π_j is a 3D vector $[x_j, 0, z_j]$. Creating the dictionary requires the calculation of all received voltage values for each π_j in the target space. The j^{th} column of the dictionary is the voltage levels v_j at the EMI receiver when only the target at π_j is present. If an array of receivers is used then the j^{th} column of the dictionary is generated by stacking the voltages $v_{j,i}$ $i = 1, 2, \dots, R_N$ as $v_j = [v_{j,1}; v_{j,2}; \dots; v_{j,R_N}]$, where R_N is the number of receivers in the EMI array. Finally, each column is normalized to have norm one to weight each target space point equally. After normalization each receiver dictionary Ψ_i can be separated. Using an EMI array of receivers and creating the dictionary by stacking up their voltage recordings before normalization allows us to use the relative amplitudes between the receivers for better cross range resolution.

2.3. Location Estimation with Orthogonal Matching Pursuit

We assume that the observed signals at the receivers are linear combinations of the responses from each target alone, thus the inter-target interaction is negligible. In this case, the following procedure is used to locate the targets:

1. Observe \mathbf{d}_i , $i = 1, 2, \dots, R_N$ voltage values at each receiver i ; so $\mathbf{d} = [\mathbf{d}_1; \dots; \mathbf{d}_{R_N}]$. Initialize row and column index sets: $\Lambda_{0,r} = \emptyset$ and $\Lambda_{0,c} = \emptyset$, the residual $\mathbf{r}_0 = \mathbf{d}$ and the loop index to $t = 1$.
2. Generate projection matrixes $\mathbf{P}_i = \mathbf{r}_i * \Psi_i$ where the operator $*$ means columnwise convolution. Sum individual projection matrixes $\mathbf{P} = \sum \mathbf{P}_i$

3. Determine the row and column indexes $\lambda_{t,r}$ and $\lambda_{t,c}$ for which \mathbf{P} is maximized.
4. Update the index sets $\Lambda_{t,r} \leftarrow \Lambda_{t-1,r} \cup \lambda_{t,r}$ and $\Lambda_{t,c} \leftarrow \Lambda_{t-1,c} \cup \lambda_{t,c}$
5. Find the weights \mathbf{c} of the least-squares problem $\min \|\mathbf{d} - \sum_{k=1}^t \mathbf{c}(\lambda_{k,c}) \Psi_{\lambda_{k,c}}\|_2$
6. Compute the new residual using the least-squares weights \mathbf{c} : $\mathbf{r}_t = \mathbf{d} - \sum_{k=1}^t \mathbf{c}(\lambda_{k,c}) \Psi_{\lambda_{k,c}}$
7. Increment the loop counter: $t \leftarrow t + 1$
8. If the stopping criteria has not been met, return to Step 2.

One can halt the procedure when the norm of the residual \mathbf{r}_t declines below a specified threshold which could be selected based on the noise energy in the received data. The target location information is stored in the row and column index sets $\Lambda_{t,r}$ and $\Lambda_{t,c}$. The row index set $\Lambda_{t,r}$ shows the shift in the scan direction from the $y = 0$ slice. The cross range information is stored in $\Lambda_{t,c}$. The cross range and depth of the targets are $\pi_{\Lambda_{t,c}}$.

3. RESULTS

To demonstrate the steps of the algorithm, consider a 2D simulation that uses a simple head with only one receiver, as in Fig. 7(a). The simple head scans with $x = 0$ cm from $y = -30$ cm to $y = 30$ cm with 1 cm increments. Assume there are two metal spheres at $(0, -19, -3.5)$ cm and at $(0, 11, 6.5)$ cm as shown in Fig. 6(a). As the simple head scans the region the recorded voltage values with a signal to noise ratio (SNR) of 20 dB is shown in Fig. 6(b).*

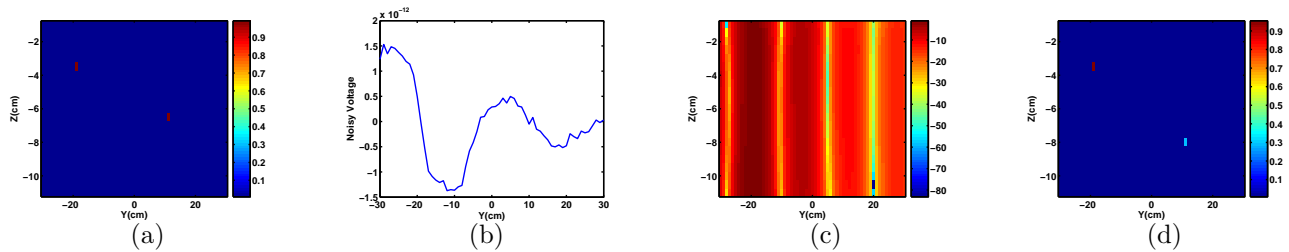


Figure 6. (a) Target space containing two targets. (b) Noisy voltage measurements (c) Projection of the measurements to each column of response dictionary (d) OMP result.

The EMI response dictionary is created with a resolution of 1 cm in y and 0.5 cm in z . One possible solution is to directly check the projection values of the received voltage measurements to each column of the EMI response matrix. Figure 6(c) shows the image containing these projection values in dB scale. It can be observed that it is directly very hard to extract the locations and the number of targets from direct projections. However, the OMP selects two targets at $(0, -19, -3.5)$ cm and $(0, 11, 8)$ cm. Although the depth information for the second target is 1.5 cm off, the locations and number of targets could be extracted with an acceptable error margin. The following results also indicate that using multiple receivers increases the accuracy of cross-range estimation.

3.1. Laboratory Depth Estimation with Quadrapole Head

To test the proposed algorithm with experimental data the quadrapole sensor in Fig. 7(a) is built. The simple quadrapole sensor is placed with its center at $x = y = z = 0$ and a metal sphere of diameter 0.5" is scanned along the track shown in Fig. 7(b) from 2 to 35 cm above the sensor level. The air response of the target-free environment is also measured and subtracted from the measurements with the target to reduce the effect of any background, e.g., moving devices and the laboratory room. The proposed algorithm is applied to air response subtracted raw data. The estimated depth values for the quadrapole sensor are shown in Fig. 7(c).

It can be observed that using the quadrapole sensor allows estimation of most depths very accurately. It is important to note here that the target is a metal sphere which matches with the model we used in dictionary generation. Also the noise level in the laboratory data is minimal once the air and lab responses are subtracted.

*Here the two targets are assumed to be far enough apart so that the interaction between them is negligible.

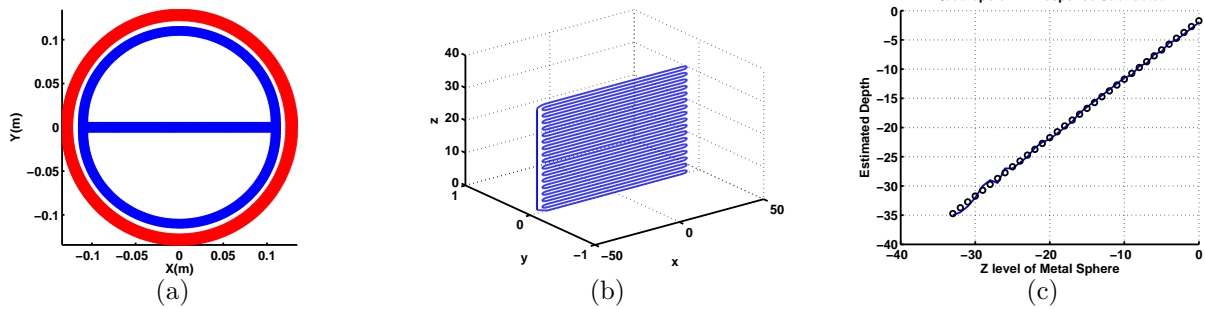


Figure 7. (a) Single Quadrapole Sensor, (b) Metal Sphere Track, (c) Depth estimates using quadrapole data.

3.2. Noise Performance

To analyze performance versus additive noise, the algorithm is applied to data created with targets at different depths from 0 to 20 cm and with varying noise levels from 10 to 50 dB. For each noise level and target depth, zero-mean gaussian noise is added to the data model for the given depth. Then the depth of the target is estimated for 100 independent trials with the proposed method. Figure 8 shows the variance from the true target position for the quadrapole sensor at each SNR level and target depth. It can be observed that even for

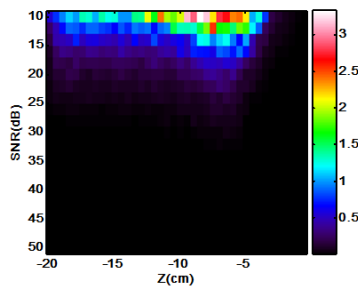


Figure 8. Variance of the depth estimates for varying levels of SNR and for targets at different depths using a single quadrapole sensor.

the case of 10 dB SNR the standard deviation of the depth estimate for the quadrapole sensor is around ± 2 cm. As the SNR increases the estimates get better as expected.

3.3. 3D Experimental Lab Results with the Quadrapole Array

A quadrapole array with three receivers and one transmitter coil, as shown in Fig. 2, is built for enhanced 3D target localization. The quadrapole array is held fixed at $x = y = z = 0$ and targets like a metal loop and an anti-personnel land mine are scanned to collect the EMI measurements.

In the first experiment, the target is a loop of 22 AWG wire with a diameter of 31.8 cm oriented so that the axis of the loop is z directed. The target is positioned at three different cross range values $x = (0.02, 0.17, 0.32)$ m. For each cross range, the target is moved in down range from $y = -50$ to $y = 50$ cm with 0.5 cm increments and from $z = -8$ cm to $z = -20$ cm with 1 cm increments from the level of the array. A dictionary using a z oriented loop target model is generated. Figure 9 shows the true and estimated depth, cross range and down-range values for the target. The location of the target is estimated relatively accurately for most of the cases even when the target is not directly under the center receiver.

Next a more interesting target, a low-metal anti-personnel mine, is tested. In this case, different cross ranges with $x = (0.07, 0.17, 0.27)$ were measured. The target was moved from $z = -7.5$ cm to $z = -28.5$ cm in 1 cm increments, and from $y = -50$ to $y = 50$ cm in 0.5 cm increments. A dictionary of responses including targets at $z = 1, 2, \dots, 30$ cm, and cross ranges from $x = -18$ to $x = 50$ cm with 2 cm increments is generated. Hence,

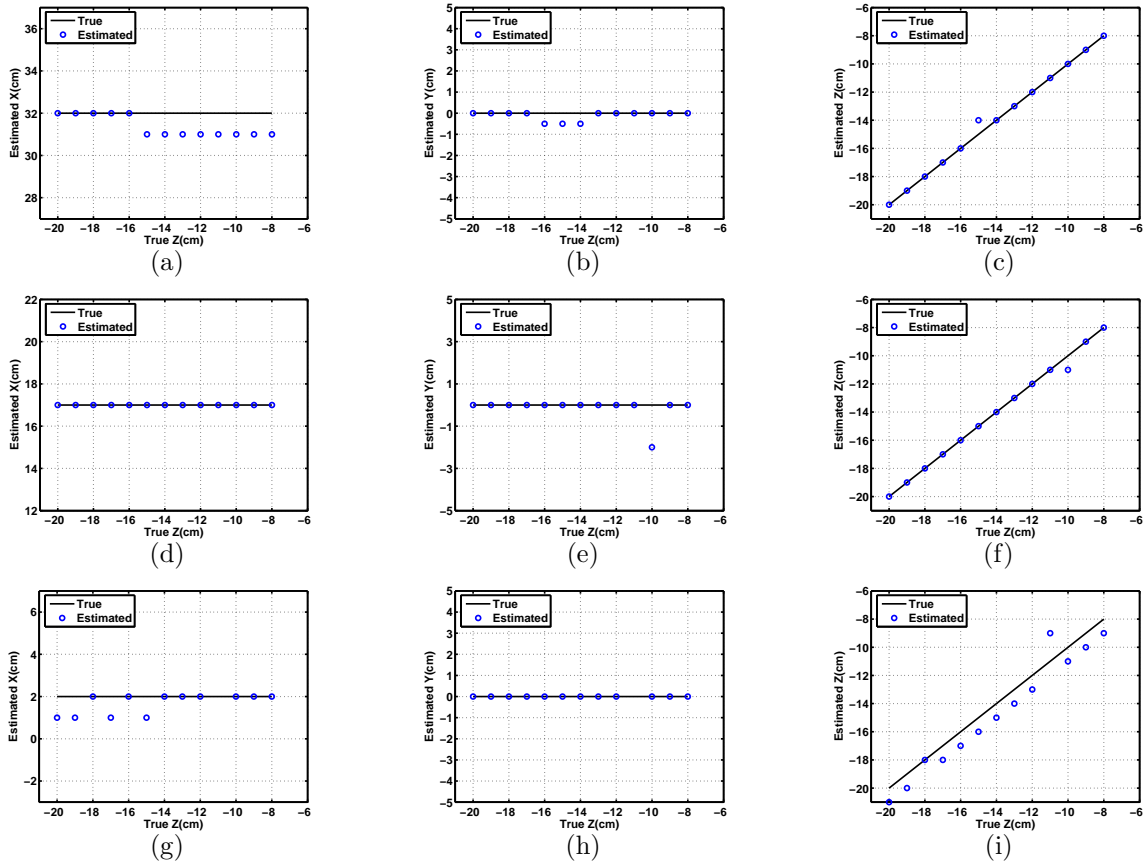


Figure 9. Location estimates for the coil target at (a,b,c) cross range $x = 7$ cm, (d,e,f) cross range $x = 17$ cm, (g,h,i) cross range $x = 27$ cm.

the exact target depths and cross ranges are not in the dictionary. A loop target model oriented in z direction is used for dictionary generation as in the loop target case. Note that the target polarization tensor is not known, and may be different than the loop target model used in dictionary generation. Despite these facts the location estimates obtained for varying cross ranges shown in Fig. 10 indicate ± 2 cm accuracy until the target depth is 17 cm. For depths below 17 cm, the estimation performance degrades. The cross-range estimation is also successful for depths less than 20 cm. In most of the cases, the down-track location estimate is very accurate.

3.4. 3D Field Data Results with the Quadrapole Array

The proposed algorithm is tested with the data collected with the quadrapole array shown in Fig. 2 at a field site over several buried targets. Each target is buried at different grids, and each grid is scanned with the array. The grid size is approximately $1.5\text{ m} \times 1.5\text{ m}$. The array is held approximately 1" above the ground level. Figure 11 shows the collected measurements from the three receivers taken by scanning a grid containing a low-metal anti-personnel mine buried approximately 2" depth from the ground level.

The target is close to the center of the grid and the quadrapole array is scanned across the grid. Hence, the voltage level in receiver 2 (center receiver) is much higher compared to the level in receivers 1 and 3. When the proposed algorithm is applied to measured data as in Fig. 11, the location of the target is estimated as $(x, y, z) = (0, 0.01, -0.08)$ m which is very close to the expected location of the target $(x, y, z) = (0, 0, -0.08)$ m. Here the origin of the coordinate system is on the surface of the soil at the center of the grid; x is the cross-range coordinate, y is the down-range coordinate and z is the vertical coordinate. The location estimates for five additional occurrences of the same type of AP mine are shown in Table 1.

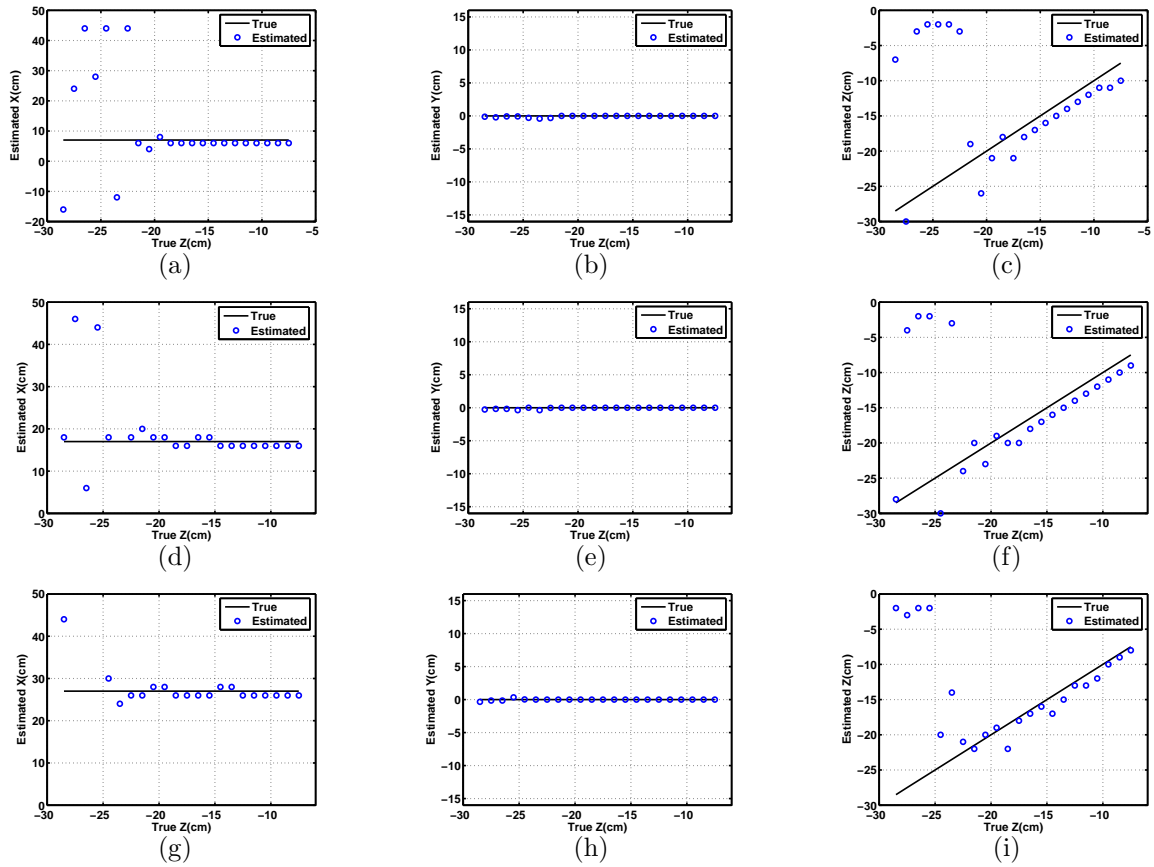


Figure 10. Location estimates for the anti-personnel mine at (a,b,c) cross range $x = 7$ cm, (d,e,f) cross range $x = 17$ cm, (g,h,i) cross range $x = 27$ cm.

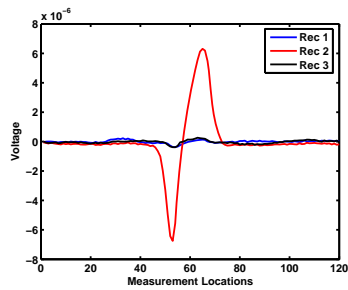


Figure 11. Imaginary part of the 11th frequency component for all three receivers.

Table 1. Field Data Location Estimates

Grid No	Expected Location (x, y, z) (m)	Estimated Location (x, y, z) (m)
1	(0, 0, -0.05)	(-0.01, 0.01, -0.06)
2	(0, 0, -0.05)	(-0.03, -0.01, -0.07)
3	(0, 0, -0.05)	(-0.02, 0.00, -0.05)
4	(0, 0, -0.08)	(0.05, 0.03, -0.11)
5	(0, 0, -0.08)	(-0.01, 0.02, -0.09)
6	(0, 0, -0.08)	(0.00, 0.01, -0.08)

It can be observed that in the field measurements the target locations and depths could be estimated to within approximately ± 3 cm. It is important to note that the approximate depth information is from the top of the AP mine, not from the metallic part. Also there might be small changes due to the burial process, or from targets being buried so long that their locations might change slightly. Nevertheless, the proposed method provides promising depth estimates in the tested field data.

4. CONCLUSIONS AND FUTURE WORK

A location estimation algorithm based on OMP using EMI data is proposed. Our initial tests on simulated, laboratory and field data indicate that target depth information can be extracted from EMI data with small errors. However, in a few cases the error can be significantly greater when the target is a poor match for the target model used in the dictionary. We are working to generalize the technique so that it is applicable to a wider range of targets.

5. ACKNOWLEDGMENTS

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