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A multi-sensor network for direction finding of moving ferromagnetic objects inside water by magnetic anomaly

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ABSTRACT

In this study, it is aimed to detect remotely the direction and the velocity of a moving object inside water by magnetic anomaly by the use of a multi-sensor network. This study is the extension of single sensor case the results of which are previously published. A three-step approach is used for finding the direction and the velocity of a moving object inside water. First, a uniform magnetic field is established in the test bed that is developed to simulate the practical environment. By the use of this test bed, the magnetic field created is determined. Second, the characteristic relations between the parameters depending upon the length of the ferromagnetic object, magnetic permeability and the direction of the motion of the object appearing in the model of the voltage variation and the direction angle are obtained. Third, a multi-sensor network is utilized for the determination of direction and velocity of any moving object inside the environment. The multi-sensor network produces a moving fixed magnitude voltage wave. The effects of the material magnetic permeability and the length are also studied in this work. It was seen that the relative permeability and the length could affect the magnitude of the wave obtained but not the shape of it. It is seen that the peak of the wave magnitude remained fixed throughout the direction of the motion of the moving ferromagnetic object even the permeability and the length of the object are different. This method clearly shows good results and the direction and the velocity of motions of ferromagnetic objects with different length and magnetic permeability inside water can be detected with high accuracy. It was seen that the number of the sensors and the way to deploy them were important for obtaining the fixed magnitude moving voltage wave in the region. This method is also suitable for the determination of material from which an object is produced.

1. Introduction

In this study, we develop a method to detect the direction and velocity of a moving object inside water by the use of multi-sensor network by magnetic anomaly. The works made previously by some researchers are depended on gathering information by a single magnetic sensor [1–5]. The theory and applications on magnetic sensors can be found in [6,7]. Now, technology is mature enough to create a multi-sensor network for this purpose [8–11].

In early days of sensor network studies, a good classification of sensor networks had been done [8]. Also in [9], the sensor networks have been classified as four different types based on the main tasks that are the monitoring, the event detection, the tracking and object classification. Our work can be considered as the use of multiple sensors for monitoring and tracking purposes in addition to the detection of moving objects. In [10], for example, a vehicle tracking application by thousand of nodes in a large area

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has been introduced. In [12–14], a probabilistic approach for the tracking of moving targets with distributed sensor has been applied. In our application, we mostly concentrate on the detection and identification of moving objects inside water or see environments Characteristics of our application are that the region of movement is known and the speed of the object is not high compared to the calculation time. Therefore, the deployment of the sensors in that region does not create a difficulty and there is no need to solve a self-deployment problem.

However, in general, the deployment is not an easy problem. For example, in [15], the authors have tried to solve a scalable self-deployment problem by the fluid dynamics approach. Also in [16], energy efficiency of the deployment problem has been tackled for intelligent mobile sensor networks. In order not to diverge from our main purpose, we deployed the sensors in a regularly arranged grid network in the measurement environment and we concentrate on the determination of mainly the direction and velocity of the moving objects by the use of magnetic anomaly. Our approach can also provide a good method for the determination of the material from which the moving object is made and the length of it. In this paper, because of the limitation of the space of the paper, we give only the direction and velocity determination method as an example. The parameters, material type and length, can be identified in similar fashion. The principles for the determination of these parameters can be found in our previous study [1].

In the studies of [17–19], some kinds of potential fields such as light, chemical pollution or nuclear contamination have the attraction capability for mobile sensor networks. The sensors move to the sink points of the potential fields. However, in our system, instead of moving the sensors, the object to be detected moves and creates modifications in the field itself. And we utilize this change for gathering information. Somehow similar but a reverse type of application compared to the aforementioned applications is applied in our work.

The purpose of this work is to prove that the motion, actually the direction and the speed of a body such as a submarine in some critical areas such as the straights made of ferromagnetic material can be detected. The experimental studies whose aims solely are related to the detection of the motion of the bodies inside the water are carried out inside a tank having a dimension of 1 m × 1 m × 1 m. In this study we simulated the earth magnetic field distribution by a homogeneous magnetic field created by the Helmholtz coils across the tank.

In case the model used in this work is to be applied to a real application, there is no need to create a homogeneous magnetic field distribution in addition to the magnetic field of the earth itself as it was done during the experiments. As we imagine that the earth magnetic field is already available in the environment. However, since the magnetic field of the earth has a DC nature, the amplitude of it is low, the distribution is not homogeneous everywhere and since the disturbances caused by the electromagnetic interferences are available under water, it is necessary to take extra precautions in order to overcome these undesirable effects. These precautions include signal processing and filtering and selection of proper sensors. We are planning to develop such studies for our future research works. One of the approaches to tackle with some of these difficulties is to use a sensor network and some statistical methods as it is done in this work.

The detection of moving objects can be achieved into two basic ways. One is the “active detection” and another is the “passive detection”. Recently, there are new approaches to detect or estimate targets and their motions [1]. A sonar system that sends acoustic waves and receives the reflected waves inside the water is an example of active detection systems. One of the major disadvantages of these kinds of active systems is that the detection of waves can also be detected by the target system. This is an undesirable way of object detection. The requirement, in most cases, is detection of objects without detected. This deficiency can be overcome by the passive detection approach. Another disadvantage of using active detection is the disturbance of the active acoustic wave by the effects such as turbulences in the sea, turbidity or multiple jumping. It is preferable to use a way that is not affected by external events but only the object itself. This is another requirement for us for the detection of the object with high certainty. As it is showed in [1] that one of the methods applied for satisfying these requirements is the utilization of magnetic anomaly. In that paper, a single sensor positioned carefully in a suitable location inside homogeneous magnetic field is used to detect the moving object. We are now extending our approach. In this paper, we establish a multi-sensor network for the detection of moving objects. The main concern is to build a practically applicable system that can reinforce the information by the utilization of data from more than one single sensor. The use of multi-sensor network has another advantage over the single sensor case. As it is also mentioned in [6,7], some of the ferromagnetic materials available in the earth can give rise to a background noise and interference signals on the sensor. In our current approach, using a multi-sensor network and a statistical way of determining the direction angle and the speed vector can smooth by summation and averaging the data and can improve the reliability of the results obtained compared to a single sensor case. The effects of background noise and interference can be eliminated by the information collected from multiple sources in parallel. Our approach can also be used easily for the detection of the length and the magnetic permeability of the ferromagnetic object, i.e., we can easily determine the material from which the object is produced. That is to say, we determine the signature of any object within the measurement area.

We have a three-step approach for finding the direction and velocity of a moving object inside water. First, we establish a uniform magnetic field in the test-bed that we developed to simulate the practical environment. By the use of this test-bed, we determine the magnetic field created. Second, we obtain the characteristic relations between the parameters appearing in the model of the voltage variation and the direction angle. Third, we utilize the multi-sensor network for the determination of direction and velocity of any moving object inside the environment.

In Section 2, we describe the measurement environment. In Section 3, the multi-sensor network for the determination of the direction and velocity of the object is explained in detail, and the test results are given. In Section 4, the effects of the magnetic permeability and the length of the moving object are discussed and explained.

2. The test-bed environment

In our work, we use the same test-bed that we used in our previous work [1]. It is a wooden water tank having the dimensions of 1 m × 1 m × 1 m. Two Helmholtz coils have been located on opposite sides of the tank. A nearly homogeneous magnetic field having an intensity of 10^{-3} T is created within the tank. No ferromagnetic material that is likely to affect and disturb the magnetic field has been used in the structures of water tank. The sensors have been deployed on the floor of the test-bed. The arrangement of the sensors on the test-bed can be seen in the following sections.

Before the measurements related to the movement of the object to be carried out, first of all we determine the magnetic field between the Helmholtz coils by measuring the sensor voltages without a moving object inside the test-bed. As seen, the magnetic field between the Helmholtz Coils is homogeneous enough. This magnetic field simulates the earth magnetic field. It is shown in Fig. 1.

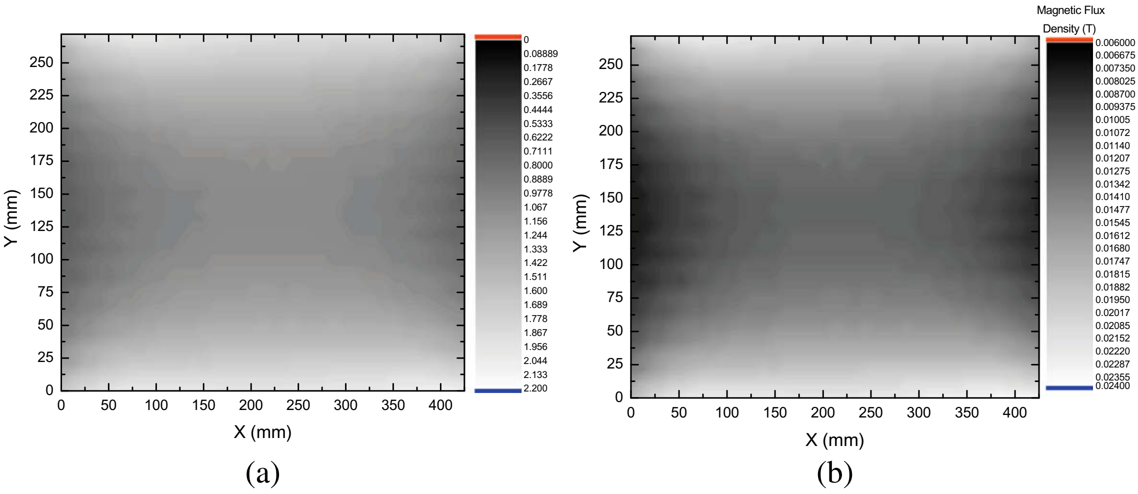
3. Multi-sensor network for the determination of the direction and velocity of the object

3.1. Procedural approach

In the previous work [1], we obtained the variations of parameters with respect to the direction of motion. We also obtained the variations of parameters with respect to the length or with respect to the magnetic permeability of the material from which the object is produced. In current study, instead of a single sensor, multiple sensors are deployed in specified intervals over the test area and a network had been established. By increasing the number of sensors, it is expected that both the direction and the speed of the objects can be determined accurately as vector quantities. Also, it is aimed that the practical application in a real environment can be achieved more easily by the use of a multi-sensor network by covering a large area of operation. In addition to them, it is also investigated the effects of the magnetic permeability and the length of the material to the output voltage of the sensors with the increase of the number of sensors. For the sake of simplicity, we show the results obtained for the detection angle and the velocity of the moving object in this paper. Someone can easily extend the results for the detection of the material or the length of the moving object as well in the same way.

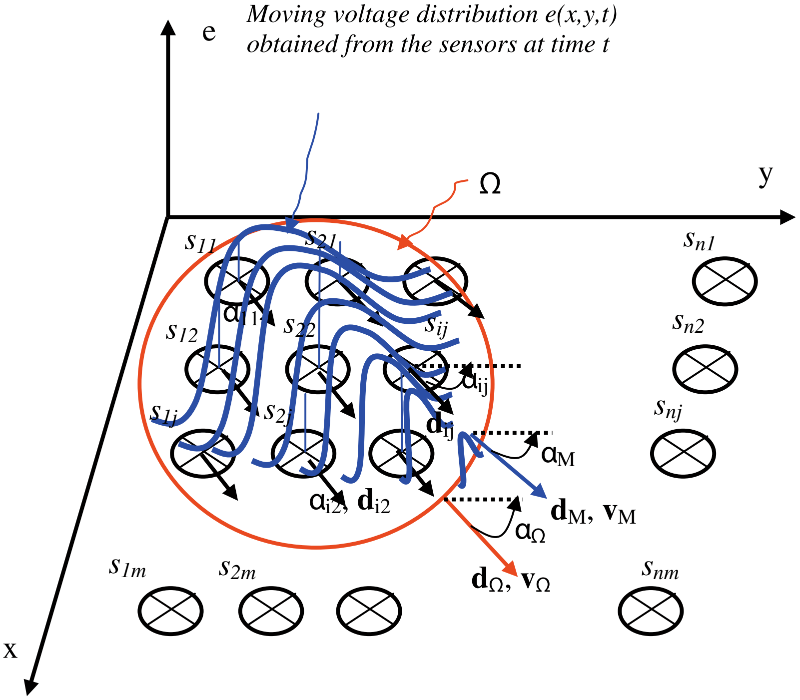
In order to explain the approach, we employ a schematic multi-sensors network on the floor of the test-bed as shown in Fig. 2.

It shows the situation where a ferromagnetic object moves over the sensor network and what happens to the magnetic field distribution of the environment. Based on our previous work [1], we intuitively think that if a ferromagnetic material is moved, then, because of the magnetic anomaly created around the moving object, the sensors inside a neighborhood region represented by a contour of Ω (let's call it as a "ball") will produce higher voltages than the resting states. As the object moves in the direction of α_a, the sensors s_{ij}'s produce voltages at their outputs depending upon the direction of the object. The number of sensors in the region Ω will depend on the speed of the material in a fixed time duration. However, if we follow the voltage changes of the successive sensors on-line with the moving object, the contour Ω surrounding the activated sensors will also move in the direction of the moving object. If the speed of the material is constant but high enough, then the ball Ω will pass through more sensors. Therefore, if the number of sensors increases and also the speed of the material increases, then the variation of the output voltages of the sensors will look like a moving wave shape of an object under a blanket as shown in Fig. 2. That



(a) (b)

Fig. 1. The homogeneous magnetic field created in the test-bed. (a) Sensor voltage and (b) magnetic flux density.



s_{ij} : ijth sensor

$\mathbf{d}_{ij}$ *: direction vector calculated at ijth sensor*

α_{ij} *: direction angle calculated at ijth sensor*

α_M *: actual direction angle of the material (moving object)*

α_Ω*: calculated direction angle of the material (moving object)*

$\mathbf{d}_M$ *: actual direction vector of the material (moving object)*

$\mathbf{v}_M$*: actual speed vector of the material (moving object)*

$\mathbf{d}_\Omega$*: calculated direction vector of the material (moving object)*

$\mathbf{v}_\Omega$ *: calculated speed vector of the material (moving object)*

Fig. 2. Deployment of the sensors and the voltage distribution at any time *t* produced at the output of the sensors as a function of (*x*,*y*).

is, the voltage distribution as seen in Fig. 2 is a wave that is also moving with the speed of υ_Ω as the object is moving.

The practical operation is as follows. Since the motion of the object is very slow compared to the speed of calculation, we have plenty of time for the calculation needed to obtain the direction and the velocity. Therefore, we easily employ two kinds of calculation procedures in the sampling periods. First one is the calculation of the angles of direction for each individual sensors based on the method given in [1]. Second one is the use of the method of dynamical tracking the voltage distribution created by the moving object at the sensors for the determination of direction angle. These two methods is applied every sampling instants of time during the operation. The application of the first method is as follows. When we deploy the multi-sensor network on the floor of the test-bed and when the object is moved in the direction of α_M, the sensors s_{ij}'s produce voltages e_{ij}'s at their outputs corresponding to the amount of magnetic anomaly produced by the moving ferromagnetic object. Every t_k ($k = 0,1,2,\ldots$), by the use of the voltages e_{ij}'s, the direction angles α_{ij}'s between the y-axis and direction vectors $\mathbf{d}_{ij}$'s of the individual sensors s_{ij}'s corresponding to the direction of the moving object are determined from the graphs of voltage distribution. An angle matrix **A** whose entries are the individual sensor angles α_{ij}'s is created in order to store the angles calculated. The sensors having voltages e_{ij}'s greater than a predetermined threshold level of voltage V_{TH} are surrounded by a contour Ω at the time t_k. The radius of Ω initially is chosen as the radius of the circular frame (that is called the "ball" as well) that contains sensors with voltages greater than the threshold determined as mentioned below. From the values of the direction angles α_{ij}'s calculated from the measured values of the voltages of the sensors, the expected value of α_Ω which shows the moving direction of the ball Ω as shown as a vector $\mathbf{d}_\Omega$ and the variance of the direction angles α_{ij}'s are determined from Eqs. (1) and (2).

The expected value and the variance of the α are

$$\alpha_\Omega = E(\alpha_{ij}) = \frac{1}{n_\Omega}\sum_{j\in\Omega}\sum_{i\in\Omega}\alpha_{ij} \tag{1}$$

$$\sigma_\Omega = \sqrt{\frac{1}{n_\omega}\sum_{j\in\Omega}\sum_{i\in\Omega}(\alpha_{ij}-\alpha_\Omega)^2} \tag{2}$$

As we said, the ball Ω containing the sensors with voltages greater than the threshold value moves in the direction of $\mathbf{d}_\Omega$ with the speed of $\mathbf{v}_\Omega$. After initial setting of the radius of the ball and obtaining the expected value and the variance of the direction angle α_Ω, we see that it is reasonable to choose the minimum radius of the ball as

$$\min(r_\Omega) = \frac{\sigma_\Omega}{2} \tag{3}$$

This criterion is well enough to use during the overall operation of the system. Because, using the standard deviation σ_Ω as the radius of the ball Ω will give a base for it, reduce the number of sensors to be taken into account and facilitate the calculations.

The second method is a dynamical approach that we think it as the main way of determining the direction. But here we use the results of both methods in parallel. In this method, a virtual deployment of the sensor network is created within the computer. The determination of the angle and the velocity are carried out by the use of this virtual sensor network. We plot the distribution of the voltages collected from the sensors on the computer screen. The plots are drawn by interpolation. A smooth distribution is created on the screen. The use of this plot during the determination of the direction and velocity minimizes the error in case the actual sensor network is used. As you notice that the actual sensor network spatial resolution is 9 × 96. However, the resolution of the virtual sensor network depends on the resolution of the computer screen if we map the measured data of voltage distribution collected from sensors onto the screen after appropriate interpolation. As we will see in the practical application, the voltage distribution is like a moving hill on the screen. The ridge of it is used for the determination of the direction of motion. The algorithm is as follows:

- Read the sensor network row by row.
- Find the maximum voltage of the row.
- Calculate the difference between the maximum values of the consecutive rows.
- Determine the direction vector $\mathbf{d}_\Omega$.
- Repeat the process.

The speed of the ball is a vector quantity with the direction of the moving object. That is,

$$\vartheta_\Omega(t) = \vartheta_M(t) \tag{4}$$

One of the additional important variables is the speed of the moving object. We can determine the speed of the moving object with the help of the speed the moving wave. The direction of the speed vector is the same as the direction determined by the angle of α_Ω. The norm of the speed vector can be found from the distance between two sensors successively producing the greater voltages and the time elapsed between these two successive activations, That is,

$$|\vartheta_\Omega(t)| = d[s_{ij}, s_{km}]\cdot\Delta t \tag{5}$$

where $d[\cdot,\cdot]$ is the distance either between the two rows or between the two columns or between the two successive diagonal sensors (i.e., the pixels) of the virtual sensor network. During the operation of the system $d[\cdot,\cdot]$ can be determined by the help of the direction vector $\mathbf{d}_\Omega$ as follows:

$$\begin{aligned} d[s_{ij}, s_{km}] = \min\big[&\mathbf{d}_\Omega\cdot\mathbf{d}_{\text{row}-1}, \mathbf{d}_\Omega\cdot\mathbf{d}_{\text{column}-1}, \mathbf{d}_\Omega\cdot\mathbf{d}_{\text{diagonal}-1},\\ &\mathbf{d}_\Omega\cdot\mathbf{d}_{\text{row}+1}, \mathbf{d}_\Omega\cdot\mathbf{d}_{\text{column}+1}, \mathbf{d}_\Omega\cdot\mathbf{d}_{\text{diagonal}+1}\big] \end{aligned} \tag{6}$$

where $\mathbf{d}_a\cdot\mathbf{d}_b$ is the dot product of two vector quantities.

The normalized error between the actual and the estimated speed is

$$\Delta\vartheta(t, \alpha_\Omega, \alpha_M) \propto \cos(\alpha_\Omega - \alpha_M) \tag{7}$$

As seen, if $|\alpha_\Omega - \alpha_M| = 0$, then $\Delta\vartheta = 0$ and $\vartheta_\Omega = \vartheta_M$.

3.2. Practical application

In our study we have a sensor network that is composed of 9 × 86 sensors. Each of the individual sensors is a coil of 4250 spir made up of a copper wire having a thickness of 0.1 mm ∅. The dimensions of the sensor are as follows: the external diameter is 20 mm, internal diameter is 3 mm and the height is 5 mm. A 40 mV voltage corresponding to a magnetic field change of 1 mT is measured across the terminals of the sensor. The deployment of the sensors on the floor of the test-bed is shown in Fig. 3. The distances between rows are 5 mm and the distances between the columns are changed depending on the experiment.

The moving ferromagnetic object is made of Si–Fe. It has a length of 10 cm and a cross-sectional area of 3 × 3 cm. It was put inside the test-bed and the experimental results obtained by the actual multi-sensor network. The object was moved in the direction of the y-axis first. We observed the moving wave as seen in Figs. A and B in Appendix A. It is well suited for the expectations and the theoretical explanation given above. Fig. A shows the voltages produced at the output of the sensors as a function of (x,y) as the object moves. The process is as follows. The measurements are taken at every row. We have spatially sampled waveforms at the sampling distances of 40 mm. The first data taken is at $d = 0$ mm when $t = t_0$. The second data are at $d = 40$ mm when $t = t_1$. The third is at $d = 80$ mm when $t = t_2$, etc. As you notice that the wave moves together with the moving object. Fig. A gives an angle of 0°. Similarly, we obtained another result in Fig. B showing a motion with an angle of 45°. The movement of the voltage distribution hill and the results obtained is shown in Fig. 4. In this figure, the ridges of the hills at each sampling distance and time are shown. We take only one peak because both peaks are moving as the object is moving. The peak moves from left to right with a speed of

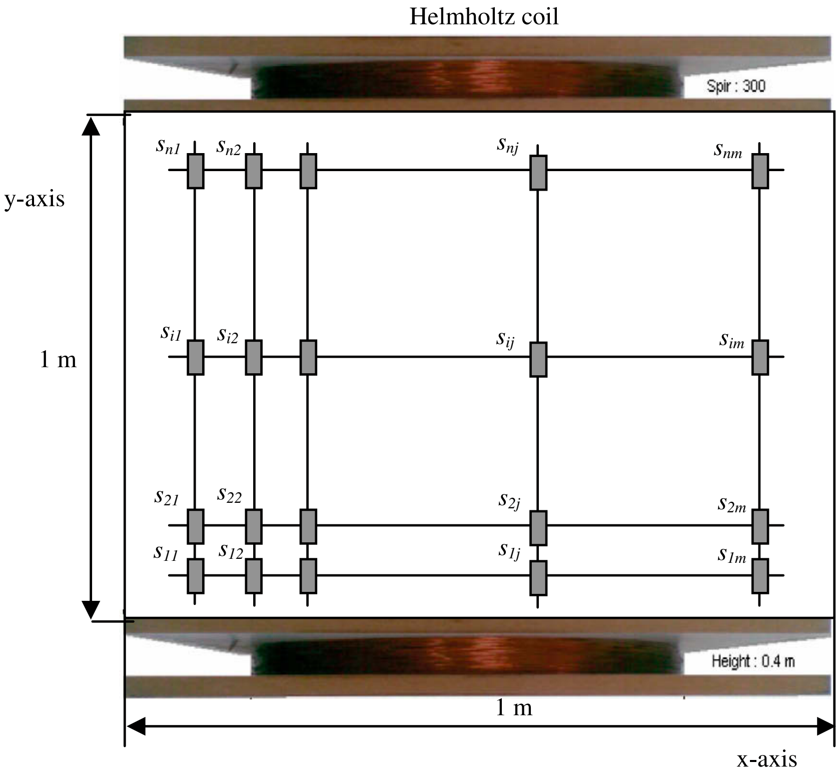


Fig. 3. The test-bed and the deployment of the sensors inside the test-bed are shown.

$v = 17.52$ mm/s as we determined. The sampling distances and the time values are shown in the figure clearly. The object reaches to the destination ($d = 440$ mm) within a time of $t = 25.114$ s. The appearance of the moving wave is similar to a moving object under a blanket.

During the experiments, we played with the speed of the object. During these different speeds, we observed that the characteristic of the wave does not change, but the magnitudes of the output voltages of the sensors change with directly proportional to the change in speed. For example, when we increase the speed 10 times higher than the previously measured one, the amplitudes of the voltages also increase 10 times. This is natural since it is the result of the Faraday law.

Two peaks are formed during the motion of the object. We noticed that the sensor reads the empty value when

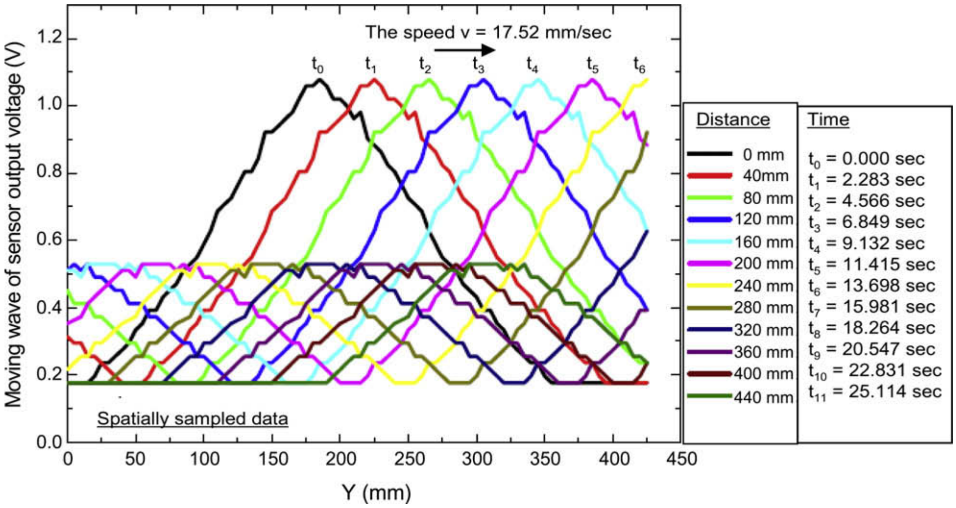


Fig. 4. The graphical representation of the motion where only the ridges of the hills are drawn.

the material is just on it. But the moving object comes to a little bit to the left or right of the sensor, two peaks are formed, one is in one side and the other is at the other side of the sensor. This is reasonable since the two ends of the sensor are the points where the change of the flux is more heavily detected. Naturally, if the moving object approaches to the end points of the sensor, then the flux lines collected will create a large variation and the voltage will rise. For example, if the object is in between the two sensors, then it is at the back of one sensor and at the rear of the other. This causes two peaks to be obtained.

In our work, the mutual inductance between the sensors does not have any worse effect to the results of the study. Naturally, there are mutual inductions among the sensors, but this effect is also available during the empty state. That is, there are mutual inductances within the empty space, and there is no relation of it with the voltage changed at the outputs of the sensors as the object moves. This can be considered, maybe, as a constant error. If we would have used a single sensor during the experiment, in this case, the constant voltage value at the empty space might have changed. But being $e+$ or $e-$ instead of an exact value of e does not divert us from the aim of the study. That is there is no negative effect of it to the results of the experiments. As seen from the graphics in Figs. A and B in Appendix A that the sensing characteristics of the sensors remain the same in the direction of movement.

4. The graphics obtained based on the magnetic permeability and the length of the moving material

We investigated and tested the effects of the magnetic permeability and the length of the moving object to the moving waveform of the motion. The voltage value of the peak of the wave decreases, as the relative magnetic permeability decreases. The voltage variation versus relative magnetic permeability is plotted in Fig. 5. The relation has a linear characteristic. It can be formulated as in the following equation:

$$V(\mu) = 1.932 + 0.00004\mu \tag{8}$$

The constant value of 1.932 V in the formula is the value obtained from each of the sensors when there is no magnetic anomaly (no moving object) available. Also it should be noticed that if the magnetic permeability decreases, the magnetic anomaly at the locations of the remote sensors decreases and the voltage outputs of the sensors becomes less. Furthermore, as the variation is linear, it is clear that the effectiveness of the multi-sensors increases.

It was observed that although the sensing characteristics of the sensors remain the same, the peak value of the voltage wave decreases as the relative length of the material decreases. The relation between the peak value of the voltage wave and the relative length of the material is linear. This relation is plotted in Fig. 6 and formulated as

$$V(L) = 1.91 + 0.009L \tag{9}$$

The value 1.91 in the formula is the value of voltage from the sensors in the case of no anomaly. As seen the variation is linear here as well. Although the detection characteristics of the multi-sensors does not vary in shape with the length of the moving object but the detection levels becomes lower as the length becomes shorter.

As a conclusion, the peak value of the voltage wave obtained from the sensors as a result of the movement of the object can be given as in the following equation:

$$V = 1.92 + \frac{(0.009 \times L)^2 + (2 \times 1.92 \times 0.009 \times L)}{(0.00004 \times \mu) + (2 \times 1.92)} \tag{10}$$

In spite of various length and magnetic permeability of the moving object, the shape of the voltage wave remains the same and the wave magnitude does not change with the direction of the movement of the object. This fact

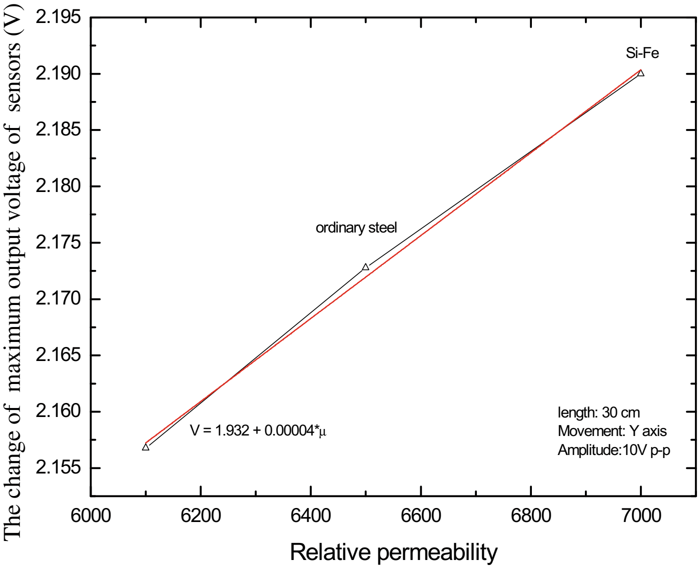


Fig. 5. The relation between the peak value of the wave in volt and the relative magnetic permeability.

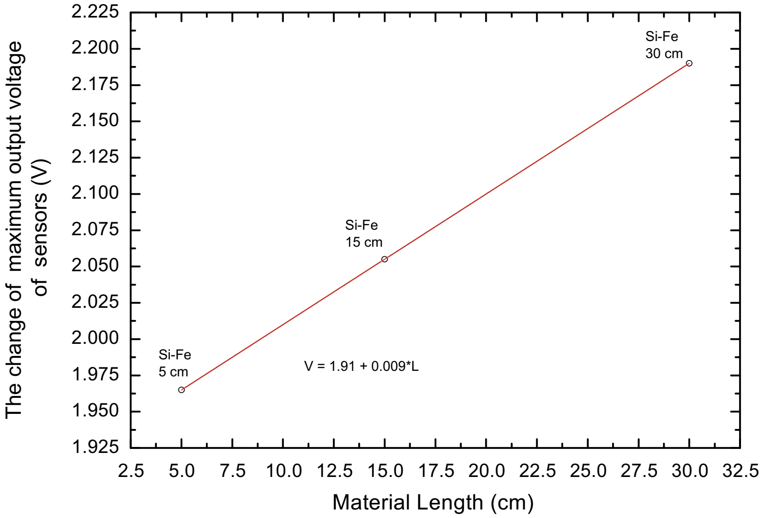


Fig. 6. The relation between the peak value of the wave in volt and the relative magnetic permeability.

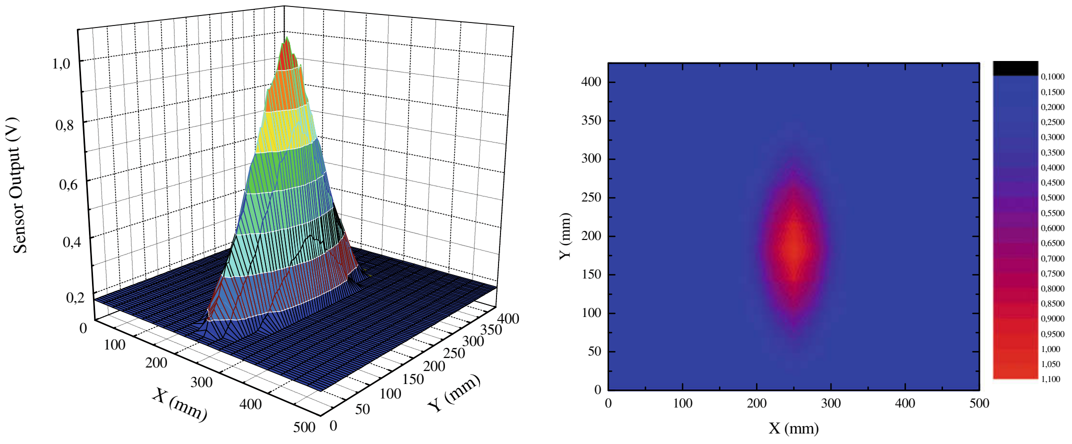
shows that the most important variables that determine the direction of motion more accurately are the number of sensors and the speed of the moving object. If the speed of the object is low and the distances between the sensors are large, then the magnitude of the moving voltage wave shows some fluctuations in the direction of motion. There are two basic reasons for this type of fluctuations. One of the reasons for this is that the sensors cannot follow the object appropriately. The other reason is the difficulty of creation of the sensor output voltage by the low magnetic anomaly change by the slow motion. However, if we increase the number of sensors and locate them closely to each other, then the fluctuations in the peaks of the voltage waves disappear and the magnitude remains constant and we can easily use Eq. (10) easily to determine the magnitude of it based on the relative length and the permeability of the material. When we obtain the moving wave as seen in the results of our experiments (Figs. A and B for example), someone looking at the Figures can easily say the direction of the moving object, since the peak value of the voltage wave remains the same throughout the direction of the motion. The speed of the wave is found recursively by the computing algorithm that follows the sensor activations based on the fixed value of the wave peak in the direction.

5. Conclusion and recommendations

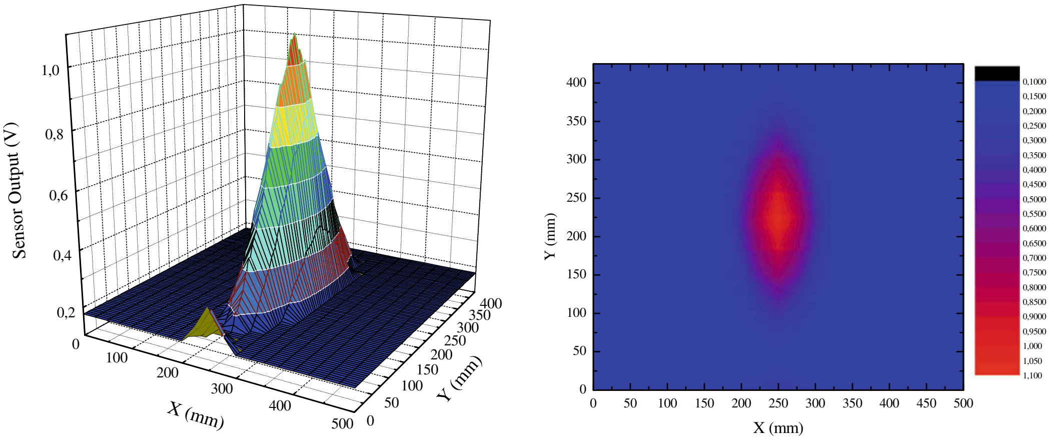
Previously developed magnetic anomaly measurement system for the measurement of the direction, permeability and length of a moving object inside water primarily for only a single sensor is extended for the use with multi-sensor network in this work. Our aim was to obtain more accurate results than the single sensor case and the quantities obtained can be represented in vector form. We used 774 sensors arranged in a 9 × 86 grid network. In this work we only gave the results for the determination of direction and velocity of the movement. However, this approach can easily be expanded for the determination of the permeability and the length of the object in similar way. These results would be useful for the signature analysis of the unknown ship or submarine. One can find the application of this method to calculate these kinds of variables in our previous work [1]. For the sake of simplicity, we only gave the results for the determination of the direction and the velocity of moving objects here. The one of the advantages for using a multi-sensor network is the elimination of uncertainties about the data obtained only by a single sensor. Statistical tools available also can easily interpret the data obtained from multiple sensors. Measurement errors and the noise effecting the measurement can be minimized. As we mentioned before, some of the ferromagnetic materials available in the earth can give rise to a background noise and interference signals on the sensor, evaluating the anomaly on the magnetic field in real time and performing this evaluation process in a differently defined field from the earth's magnetic field are necessary. In our current approach, using a multi-sensor network and a statistical way of determining the direction angle and the speed vector can improve the results obtained. The effects of background noise and interference can be eliminated by the information collected from multiple sources in parallel.

The other advantage is the deployment the sensor or sensors over the environment where the measurements are obtained. It is hard to deploy a single sensor in practical applications. The position and the orientation of a single sensor could be difficult. In our previous work, we tried to prove the concept. Therefore, we used a single sensor in that study. We saw that the approach is very useful and here, we produced a system having much more practical capabilities than the single sensor case.

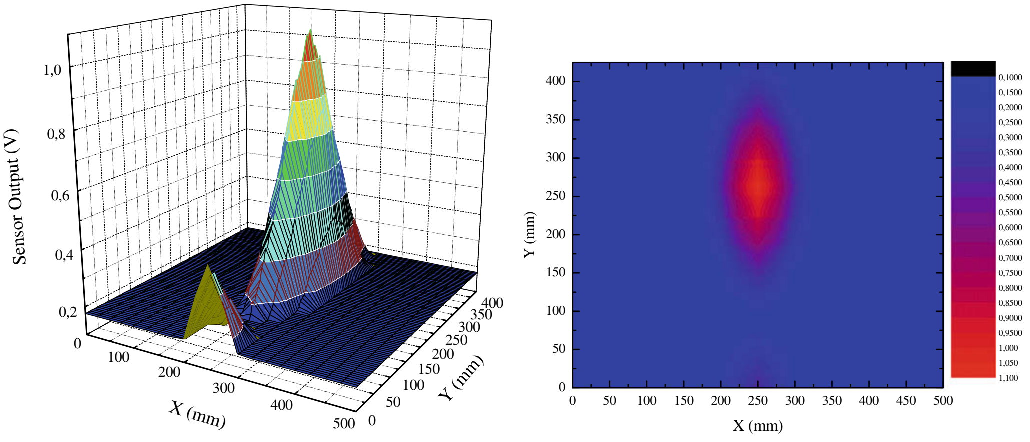
The experimental results show that the number of sensors and their spatial frequency (i.e., the distances between the sensors) are important for an accurately determination of the direction and the speed of the motion of the object. As we mentioned above, the important consideration



(a) d=0 mm , t=t_0=0 sec



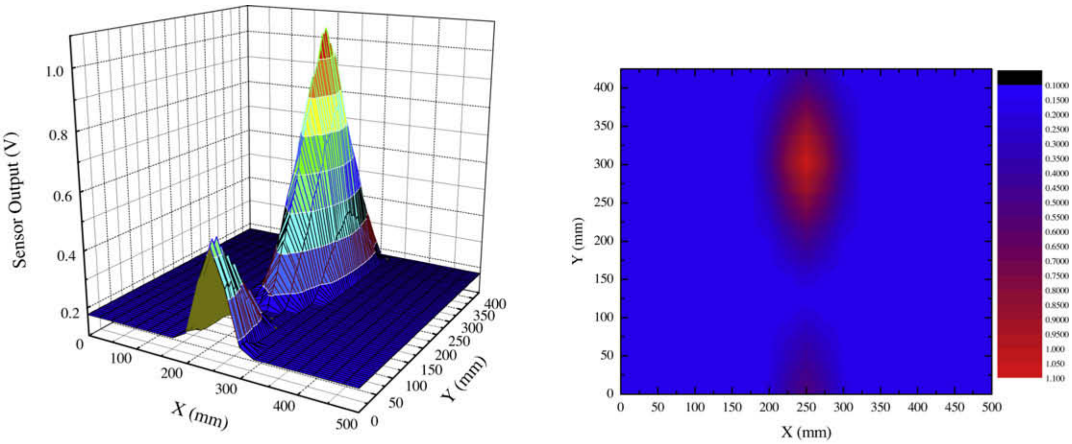
(b) d=40 mm , t=t_1= 2.283 sec



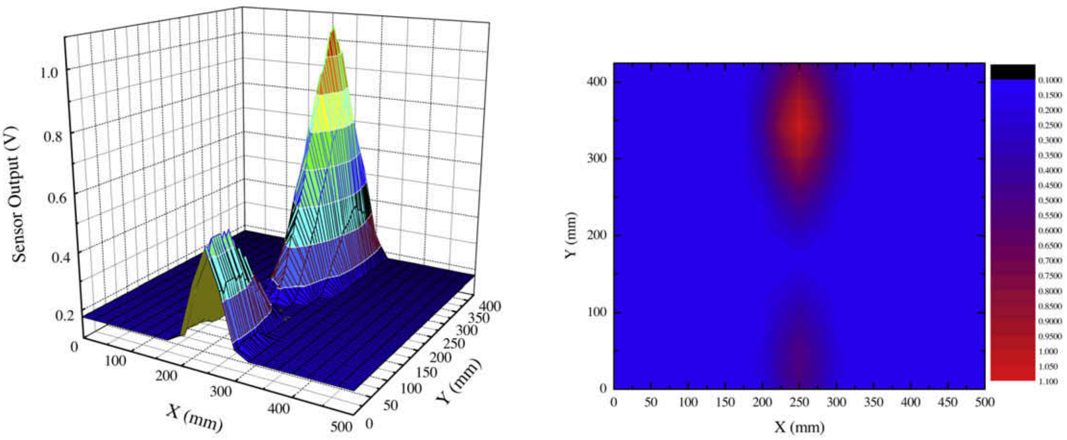
(c) d=80 mm , t=t_2= 4.566 sec

Fig. A. The results shown in graphical form of the motion of the object where the angle of direction is about 0°.

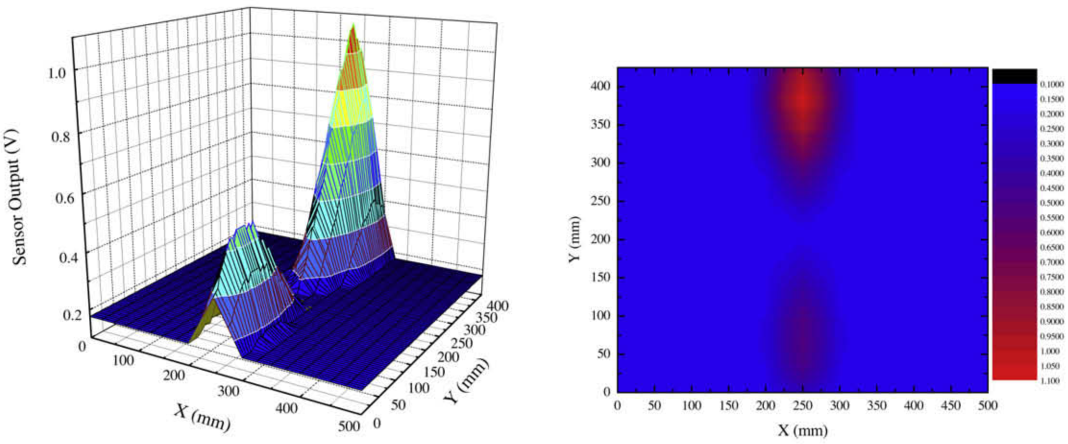
is the shape of the wave rather than its magnitude. For an appropriate deployment of the sensors, we can obtain a wave of voltage having a fixed amount of peak value throughout the direction of motion. If the sensors are not close to each other, we observe a fluctuation in the wave amplitudes. Only solution for obtaining a fixed magnitude voltage wave is to increase the speed of the object. However, the speed of the object is independent of our intervention. Therefore, only variable to control is the number of the sensors deployed. If we increase the number of sensors and



(d) d=120 mm , t=t$_3$= 6.849 sec

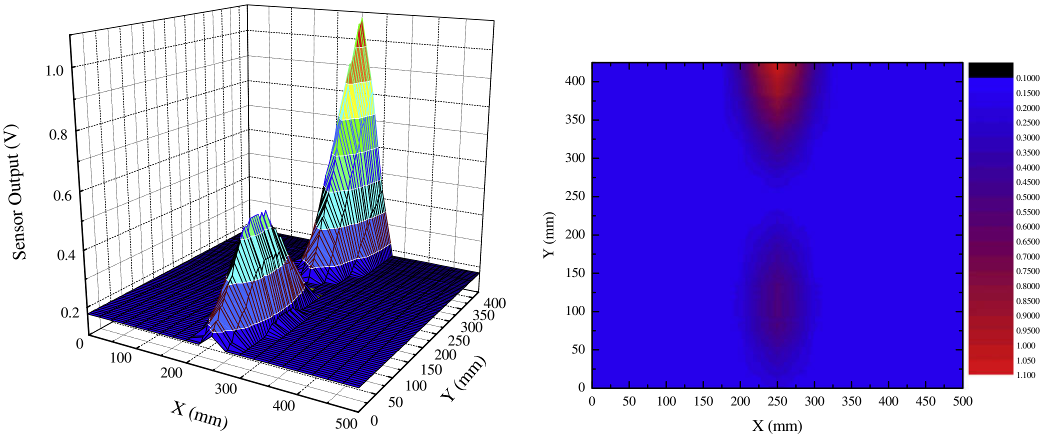


(e) d=160 mm , t=t$_4$= 9.132 sec

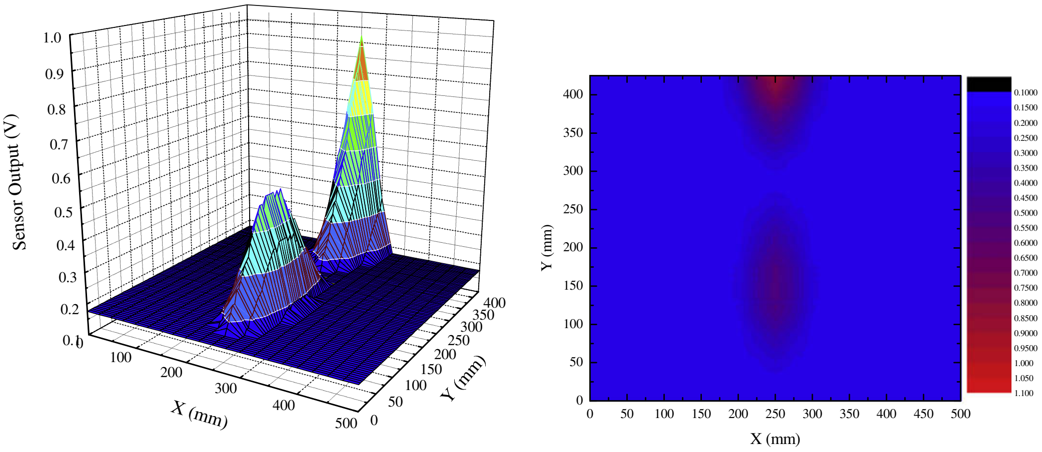


(f) d=200 mm , t=t$_5$= 11.415 sec

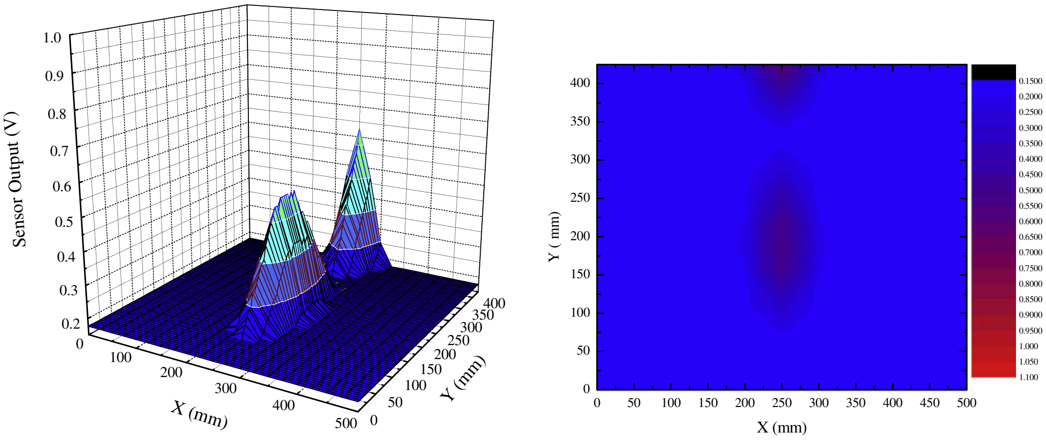
Fig. A (*continued*)



(g) d=240 mm , t=t_6= 13.698 sec

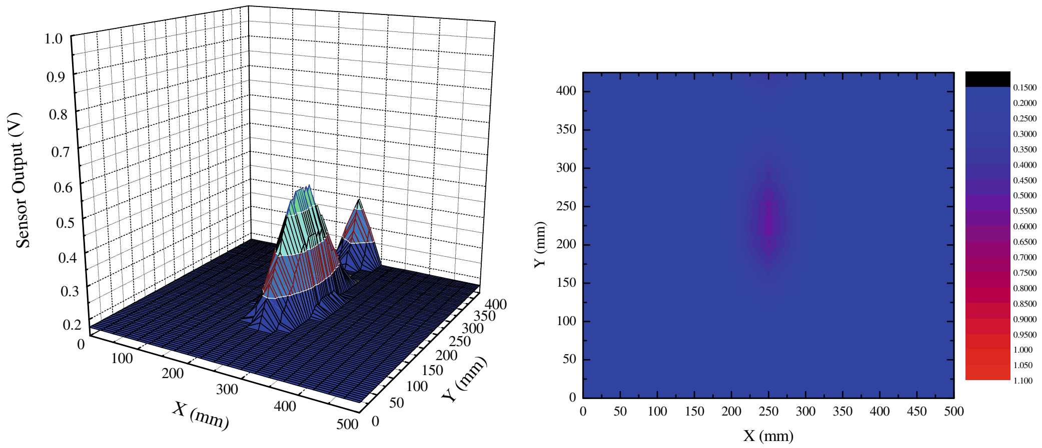


(h) d=280 mm , t=t_7= 15.981 sec

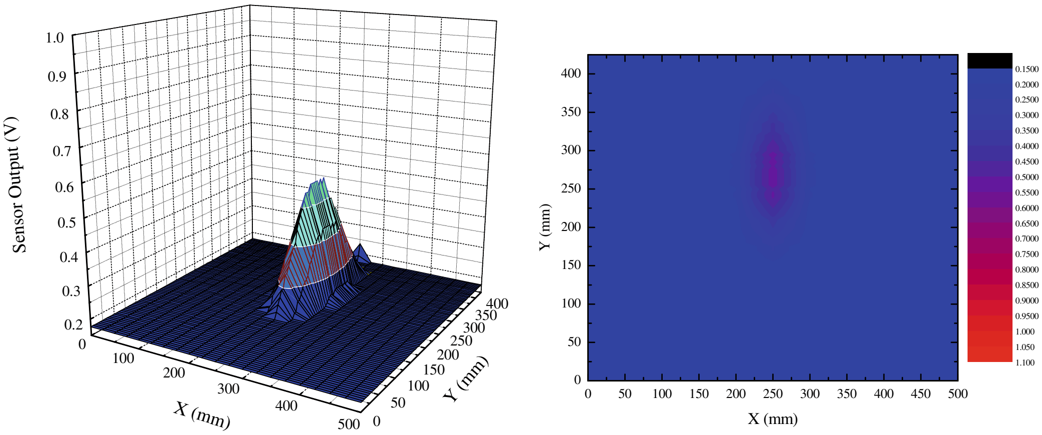


(i) d=320 mm , t=t_8= 18.264 sec

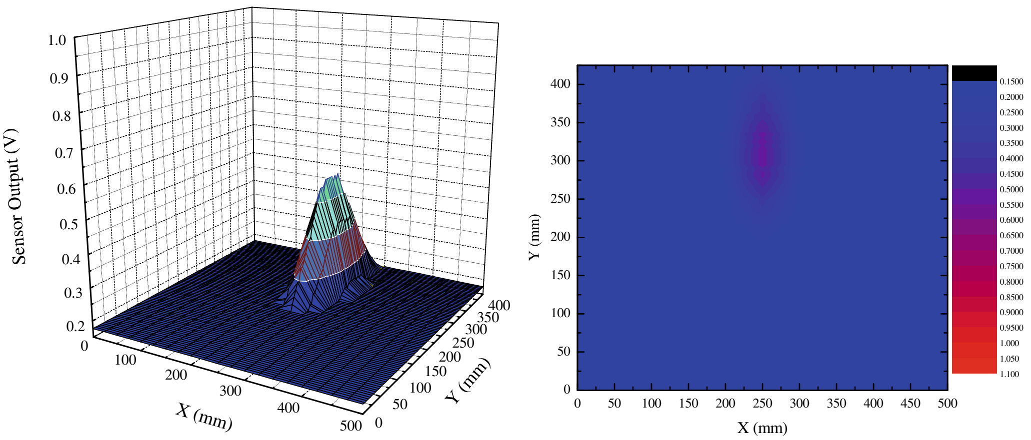
Fig. A (*continued*)



(j) d=360 mm , t=t_9= 20.547 sec

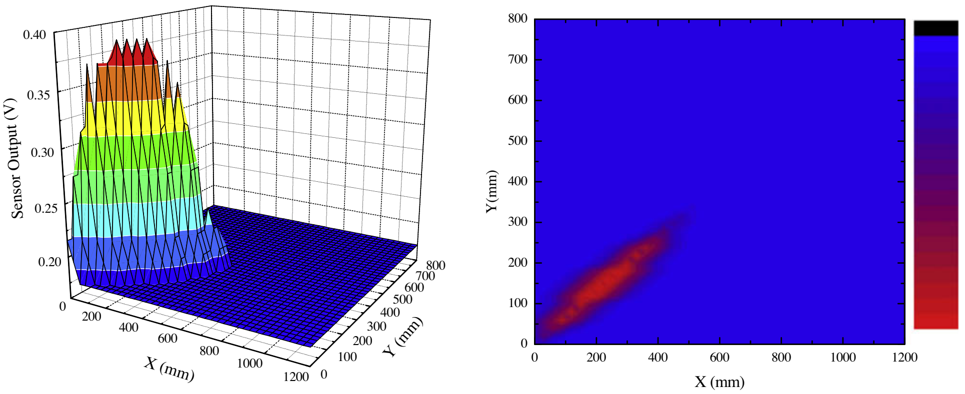


(k) d=400 mm , t=t_{10}= 22.831 sec

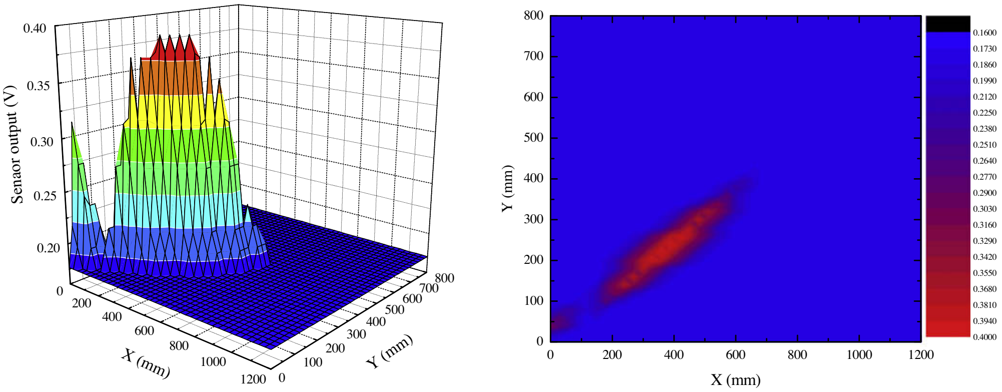


(l) d=440 mm , t=t_{11}= 25.114 sec

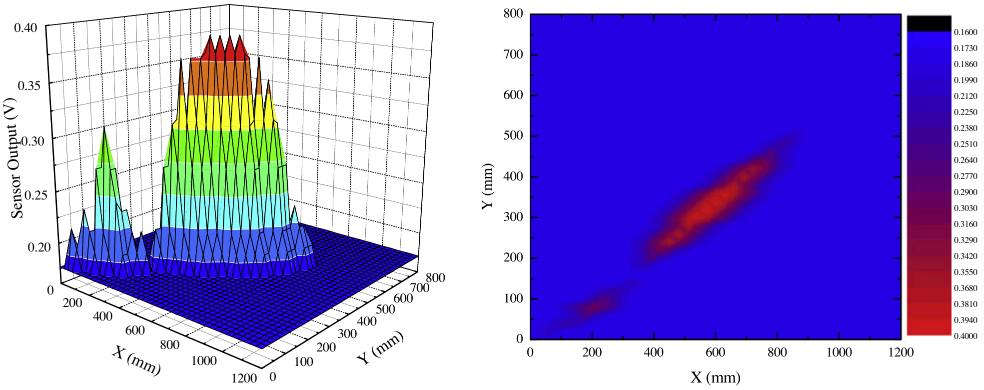
Fig. A (*continued*)



(a) d_x=0 mm, d_y=0 mm , t=t_0= 0 sec



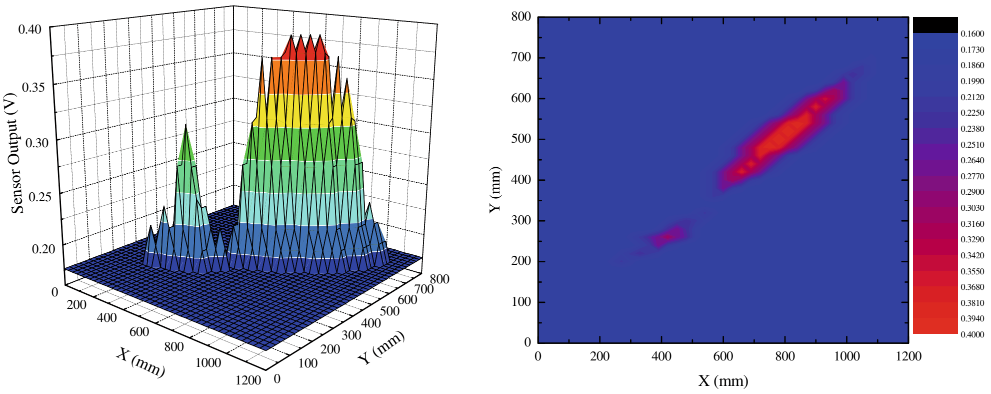
(b) d_x=200 mm, d_y=150 mm , t=t_1= 14.27 sec



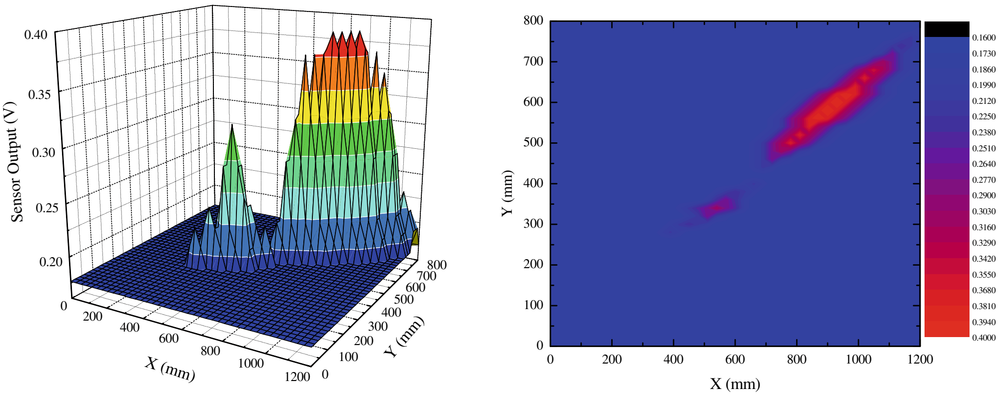
(c) d_x=400 mm, d_y=300 mm , t=t_2= 28.54 sec

Fig. B. A diagonal motion where the angle $\alpha = 45°$. The speed of the object is again $v = 17.52$ mm/s.

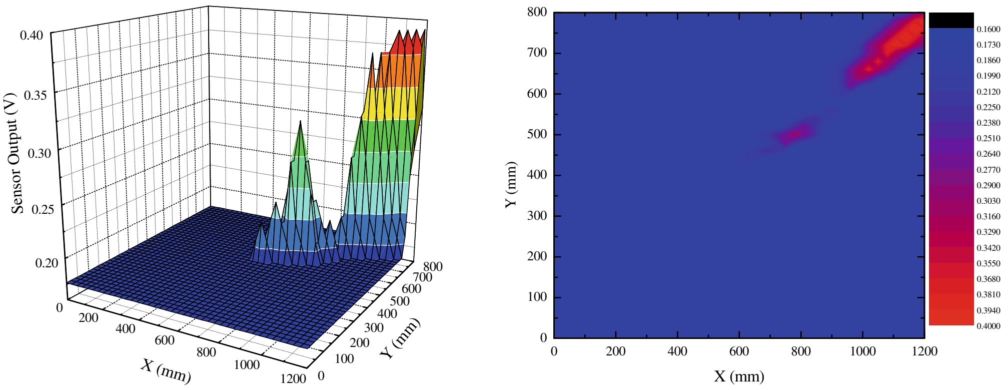
locate them closely to each other, then the fluctuations in the peaks of the voltage waves disappear and the magnitude remains constant and we can easily use Eq. (10) easily to determine the magnitude of it based on the relative length and the permeability of the material. The speed of the object affects the magnitude of the voltage wave obtained by the sensors, but we determine the direction and the speed computationally in the computer based on the activation sequence of the sensors. Therefore it is not important for us the level of the voltages obtained. Rather, it is more important for us to obtain a wave moving with a fixed magnitude as the object is moving.



(d) d_x=600 mm, d_y=450 mm , t=t_3= 42.81 sec

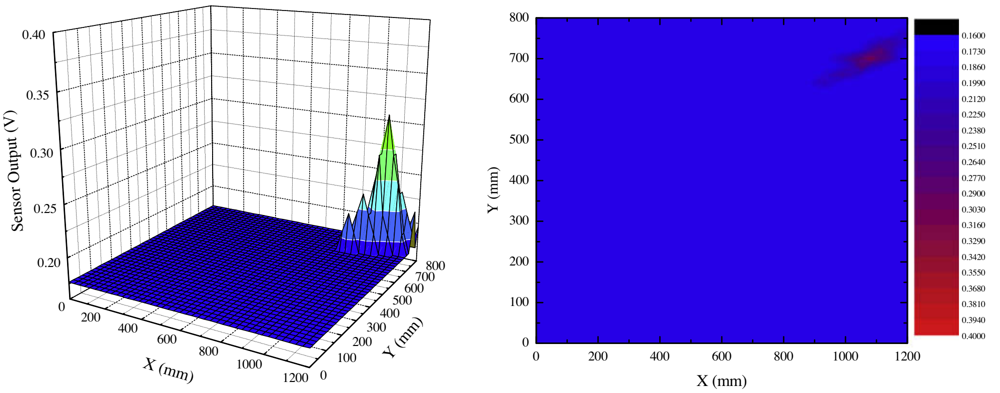


(e) d_x=800 mm, d_y=600 mm , t=t_4= 57.08 sec



(f) d_x=1000 mm, d_y=750 mm , t=t_5= 71.35 sec

Fig. B (*continued*)



(g) d_x=1200 mm, d_y=900 mm , t=t_6= 85.62 sec

Fig. B (*continued*)

Appendix A. Graphical representations of the motion of the object

A.1. The tracking in the direction of α = 0°

Notice that the voltage wave is moving in the direction of *y*-axis. The speed of which is 17.52 mm/s (see Figs. A and B).

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