Design of systems for determining the location (positioning) of objects in closed electrically conductive environments

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Abstract. Determining the location of the object relative to the observation point is an urgent task in the framework of automation of production facilities. Actively introducing systems to prevent collisions and collisions with pedestrians of self-propelled vehicles, create restricted areas, and control the movement of personnel. The variability of the task and operating conditions leads to the existence of narrowly targeted areas for which generally accepted standard solutions are not suitable. An example of such a technical field is the emergency search system for personnel under the rubble of the rock mass in the conditions of mining. The requirements set by the supervisory authorities require the search team to determine the location of the victim at a distance of up to 50 meters, with an accuracy of at least 2 meters. Issues of underground communications have already been considered in [1], [2].

1. Introduction
Systems for determining the location of objects under the rubble consist of a head unit (HU) that initiates work and determines the distance, and slave transponders - beacons. In order to save beacon charge, the search signal is emitted only upon request from the master.

![Figure 1. Description of the location system.](image)

The specific of the use of systems implies that the beacon is a compact wearable device with autonomous power, minimum overall dimensions and price. The main limitations relate to the choice of antennas and radiated power.

To solve the problem of determining the location of an object indoors, there are a large number of high-tech industrial solutions that are well described in [3]. These solutions operate in the high and ultra-high
frequency range, and the distance is estimated by the propagation delay of the signal. With high accuracy and energy efficiency, they have a significant drawback. The high frequency spreads well in space, but has a high reflectance from obstacles and poor penetration. Thus, if any obstacle caught between the transmitter and the receiver is a serious obstacle, then a layer of water or conductive rock completely deprives the possibility of work.

Existing positioning devices in conditions of high electrical conductivity use the ultra-low frequency range. Due to the limited scope, the market for such devices is relatively small, so there are no common standards, and manufacturers are developing their own solutions.

2. Practical calculations when choosing antennas

The parameters affecting the choice of the operating frequency are the amount of wave attenuation and technological limitations of the transmitting and receiving equipment. With a frequency increase, the effective length of the antennas increases, but the attenuation coefficient of the wave in the medium increases, this is clearly reflected in figure 2.

![Figure 2. The dependence of the dielectric constant on the frequency of the electromagnetic field [5].](image)

Leaving in the region of super low frequencies, it is important to take into account the specifics of the propagation of radio waves in the near zone. The near zone refers to the area around the emitter, for which \(|k \cdot r|<<1\), where \(k = \frac{2 \pi}{\lambda}\) - wave number. Therefore, \(r << \frac{\lambda}{2 \pi}\) [7].

Given that the wavelength on average is: \(\lambda_{\text{av}} = \frac{\lambda_0}{\sqrt{\varepsilon_e \mu_e}}\),

\[
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\]  

where \(\lambda_0\) – wavelength in vacuum, \(\varepsilon_e\) – electrical permeability, \(\mu_e\) – magnetic permeability. In the worst case, seawater, \(\mu_e=1\), \(\varepsilon_e=81\), at a signal frequency of 10 kHz, the wavelength will be \(3 \times 3\) km, which is more than 60 times the radius of action of the developed system.
Figure 3. Radiation of an elementary electric dipole in a spherical coordinate system.

In the near zone (induction zone), the generated electromagnetic wave is not yet fully formed. From a physical point of view, the near zone is a region of space in which the so-called quasistatic regions are of primary importance. These fields, which sharply decrease with distance from the source, continue to exist as the frequency of the exciting current tends to zero.

For the near field of an elementary electric dipole, the following relations are valid [6]:

\[ \mathbf{H} = \left( \frac{Ih}{4\pi r^2} \right) \sin \theta \]  
\[ \mathbf{E}_r = -j \left( \frac{Ih}{2\pi \omega \varepsilon_A r^3} \right) \cos \theta, \]  
\[ \mathbf{E}_r = -j \left( \frac{Ih}{2\pi \omega \varepsilon_A r^3} \right) \cos \theta, \]

where \( \mathbf{H} \) – magnetic field vector; \( \mathbf{E}_r, \mathbf{E}_\theta \) – components of the electric field vector; \( h \) – dipole length; \( I \) – current vector; \( \varepsilon_A \) – absolute complex dielectric constant of the medium; \( \theta \) – viewing angle; \( r \) – distance to emitter.

It can be seen from formulas (2–4) that the magnetic component \( \mathbf{H} \) is inversely proportional to the square of the distance \( (\mathbf{H} \sim 1/r^2) \), in contrast to the electrical component \( \mathbf{E}_\theta \), which is inversely proportional to the cube of the distance \( (\mathbf{E}_\theta \sim 1/r^3) \).

Therefore, in order to increase the range of the energy of the signal in the near field, it is advisable to use the magnetic component of the electromagnetic field. This explains the widespread use of magnetic antennas in the ultra-low frequency range.

According to the second equation of the electromagnetic field of Maxwell in integral form [6]:

...
where \( \oint_{L_{os}} E \, dl = -\int_{S_{oa}} \frac{\partial B}{\partial t} \, dS_{oa} \),

Equation (5) relates the EMF induced in the conductive circuit with the time variation of the magnetic field. EMF induced in a magnetic antenna is proportional to the rate of change of magnetic flux over time:

\[
e_H = \omega n_a \mu_0 \mu_e H S_p \sin \theta,
\]

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where \( \omega \) – circular current frequency; \( n_a \) – number of antenna turns; \( \mu_0 \) – magnetic permeability of air; \( \mu_e \) – effective relative magnetic permeability of the antenna; \( H \) – magnetic field strength; \( S_p \) – turn area.

Having analyzed formulas (2) and (6), we can conclude that in order to increase the range of the communication system, it is necessary to increase the length of the dipole and current in the transmitting antenna, as well as the area of the receiving antenna.

Despite the fact that with comparable linear dimensions of the dipole and the frame, the efficiency of the dipole is higher due to the greater radiation resistance of the dipole \( (R_{\Sigma\delta} >> R_{\Sigma\theta}) \).

\[
R_{\Sigma\d} = \frac{2 \eta \pi}{3} \left( \frac{h}{\lambda} \right)^2,
\]

\[
R_{\Sigma\b} = \frac{\eta \pi}{6} \left( \frac{2 \pi k r_0}{\lambda} \right)^4.
\]

In practice, in portable devices, dipole antennas are replaced by frame or ferrite antennas, due to their smaller dimensions.

For the convenience of calculations, the term is used - the effective height of the antenna, which is defined as:

\[
H_d = \frac{2 \pi n_a S_p}{\lambda} \mu_e.
\]

It is important to pay attention to the parameter \( \mu_e \) - the effective magnetic permeability of the magnetic antenna; it shows how many times the inductance of the antenna winding changes in the presence of a core. As mentioned above, magnetic antennas are of two types: frame and ferrite. The former most often represent a flat inductor wound on a dielectric frame, in this case \( \mu_e = 1 \). Ferrite magnetic antennas can increase the effective height of the antenna by using a core made of ferromagnetic material. In this case, \( \mu_e \) is determined based on the initial magnetic permeability of the core material \( \mu \), its geometric dimensions and the location of the winding on the core [9].

\[
\mu_e = \frac{\mu}{1 + 0.84 \left( \frac{d}{l} \right)^{1.7} (\mu - 1)}.
\]
Formula (10) is estimated and suitable for calculating ferrite antennas, in which the core diameter \(d\) is much less than its length \(l\), and the winding is located in the center. More detailed calculations are given in the source [10]. As the length of the ferrite core increases, the effective height of the antenna increases. In practice, the core should be selected as large as possible, as the design of the receiver allows. A further increase in the effective antenna height for a given rod volume can be achieved through the use of several rods, each of which is equipped with a separate winding. In this case, all the rods should be located at a distance at which there is practically no magnetic connection between the windings connected in series with each other.

Ferrite antennas are more often used as receiving antennas due to limitations on the maximum magnetic moment \((n a \cdot I)\) caused by the limiting value of magnetic field induction in materials.

\[
B_{\text{max}} = \mu_{0} \mu_{r} n a I \frac{l^2}{\sqrt{d^2 + l^2}},
\]

where \(d\) – winding diameter, \(l\) – coil length.

Thus, the main difference between transmitting and receiving antennas is the number of turns.

Magnetic field induction depends on the current in the transmitting antenna. In order to reduce consumption and compensate for the reactive component, a sequential oscillatory circuit (current resonance) is used in the generators. The quality factor of the circuit depends on the loss resistance and wave resistance. Therefore, for low-frequency systems, it is necessary to increase the inductance and reduce active losses (increase the cross-section of the wire and choose a resonant capacitance with the smallest tangent of the loss angle).

The inductance of the frame depends on the number of turns, winding thickness and diameter. An estimate of the inductance for a round frame can be made according to the formula [11]:

\[
L = 0.0002\pi D \left( \ln \left( \frac{8D}{d} \right) - 1.75 \right) \cdot 10^{-6}.
\]

It is important to know the inductance parameter when constructing both the receiving and transmitting antennas. To reduce the high-frequency components, it is necessary that the loop resistance has a pronounced inductive component.

3. Location algorithm
The problem of determining the distance between radio transmitters is solved by two methods, the first more modern Time-of-Flight (ToF), based on determining the delay of the propagated signal. Solutions are known [12, 13] but all of them are high-frequency, since the resolution of this method depends on the relative change in the phase of the signal at the measured distance, which is completely unsuitable for the low-frequency range.
Figure 4. Phase distance method.

The second method is based on measuring received-signal strength (RSS) [14]. The approximate formula for calculating the distance:

\[ d_r = \left( \frac{K}{RSSI} \right)^{1/3}. \]  

where \( d_r \) – distance in meters, \( RSSI \) – signal amplitude, \( K \) – calibration factor, dependent on environmental conductivity, analog input circuits and antennas.

The disadvantage of this method is the need for a calibration step for maximum accuracy with different electrical conductivities of the environment.

During the calibration process, with the default coefficient \( K' \), determine the distance \( d_T \), m from the mark and compare this value with the direct measurement of \( d_P \), m (using a measuring tape or laser range finder):

\[ K = K' \cdot \left( 1 - \frac{d_T - d_P}{d_T} \right). \]

Figure 5. Positioning an object using triangulation.
To reliably determine the position of an object in 2-dimensional space, it is necessary to measure the distance at least 3 observation points. Next, the system of equations is solved [15]:

\[
\begin{align*}
(X - X_1)^2 + (Y - Y_1)^2 &= D_1^2 \\
(X - X_2)^2 + (Y - Y_2)^2 &= D_2^2 \\
(X - X_3)^2 + (Y - Y_2)^2 &= D_3^2
\end{align*}
\]

(14)

4. Conclusion

The main stages of designing a system for positioning objects in conditions of high electrical conductivity of the environment are considered. The possibility of using electromagnetic waves of the ultra-low frequency range is shown.

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