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Wireless Capsule Endoscope Localization with Phase Detection Algorithm and Simplified Human Body Model

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***Abstract*—Wireless endoscopic capsules can transmit the picture of the inside of the digestive tract to the external receiver for the purpose of gastrointestinal diseases diagnose. The localization of the capsule is needed to correlate the picture of detected anomalies with the particular fragment of intestine. For this purpose, the analysis of wireless transmission parameters can be applied. Such methods are affected by the impact of the human body on the electromagnetic wave propagation that is specific to the anatomy of individual person. The article presents the algorithm of localization of endoscopic capsules with wireless transmitter based on the detection of phase difference of received signals. The proposed algorithm uses simplified human body models that can change their dielectric properties in each iteration to improve the location of the capsule endoscope. Such approach allows to reduce localization error by around 12 mm (15%) and can by used for patients of different physique without the need of the numerical models of individual body.**

***Keywords*—wireless endoscopes, human body models, Wireless localization, Wireless communication**

I. INTRODUCTION

WIRELESS endoscopic capsules are used in medicine for non-invasive imaging and diagnosis of gastrointestinal diseases. Thanks to them, medical specialist can receive images of the inside of the digestive tract. However, if any pathologies are detected in the pictures provided with endoscope, they are not supplemented with the information on their exact location. The correlation of picture with the position of endoscope is very important for the subsequent treatment of the detected disease by surgery or local drug delivery.

In recent years, various localization methods have been developed for this application. The methods presented in [1-2] base on the analysis of visual features of recorded picture. Such methods may suffer from the image disturbance due to camera obstruction and require the advanced image processing with high numerical burden. The most satisfying results are obtained with the use of algorithms that analyze the magnetic field distribution in the proximity of the transmitter [3]. The major disadvantage of such method is the need of gathering the a priori knowledge on the human body that is the subject of diagnosis process. Another methods presented in literature analyze the parameters of the wireless signal received from the endoscope, such as power, phase or delay [4]. Human body is a complex, heterogeneous object that has great influence on the propagation of electromagnetic waves [5]. This makes the analysis of wireless signal in the link between endoscopic capsule and external receiver very difficult. The conversion of signal power or its phase to a distance from the transmitter is not unambiguous transformation in the considered propagation environment. For this reason, the algorithms described in the literature are very sensitive to differences in the structure of the human body. To reduce this problem and improve localization accuracy the endoscopes are additionally equipped with inertial sensors [6] and algorithms are using digital filters such as particle or UKF (Unscented Kalman Filter) filters [7].
To locate the endoscopic capsule based on the parameters of the received signal, it is necessary to determine the distance between the capsule and the receiving nodes located on the patient's body. Upon this it is possible to calculate the geometric coordinates of the capsule. In the literature numerous methods that could be used for this purpose are presented. They base on the analysis of received signal strength [8], signal propagation time differences - TDoA (Time Difference of Arrival) [9] or phase detection of received signals PDoA (Phase Difference of Arrival) [10]. In the case of the endoscope, the parameters of the received signal are significantly influenced by the properties of body tissues such as conductivity and dielectric permittivity. Using heterogeneous numerical models of human body, which represent the exact structure of the human body and electrical parameters of the tissues, it is possible to achieve satisfactory results of endoscope capsule localization based on the analysis of radio signal parameters [10]. Such models are available in electromagnetic simulation software packages representing a single individual person. Due to the anatomical differences of each patient, this approach suffers from the lack of correspondence between the measurement results and the simulation results performed with exact model. To omit this limitation, we developed the localization algorithm that uses reduced numerical models of the body that can be dynamically adjusted to match the structure individual body.In this research simplified model with adaptive permittivity parameter was adopted to made algorithm insensitive to the different structure of the human body.

II. RESEARCH OBJECTIVES

The aim of this research is to create the algorithm that can identify three geometrical coordinates (x, y, z) of an

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endoscopic capsule equipped with a transmitter. This will determine the position of capsule in three-dimensional space basing on the analysis signal phases that were transmitted by the capsule (at the frequencies *f1* and *f2).* The signal is received by *N* receivers equipped with antennas located on the human body having coordinates u_n, v_n, w_n, where for the three-dimensional case $N \geq 4$.

In order to estimate the geometric coordinates based on the measured phase difference for two transmitted signals on different frequencies, it is necessary to estimate the distance d_N between the receiving antennas and the transmitter (Fig. 1). This requires information on the velocity of electromagnetic wave propagation in the media that depends on the electric permeability of the human body tissues through which the signal propagates reaching the antennas. In homogeneous body models, these values are known and constant for each capsule position as well as for the entire body area. Usually the average value of relative electric permittivity for human body model equals to $\varepsilon_r = 52$. Often, in simplified models the electric parameters are equal to the properties of one of the tissues (typically muscle tissue) [10]. This approach reduces the time and cost associated with expensive body scans, which for heterogeneous body models would have to be prepared for each patient separately. On the other hand, the adopted simplification significantly affects the accuracy of the estimated position of the endoscopic capsule.

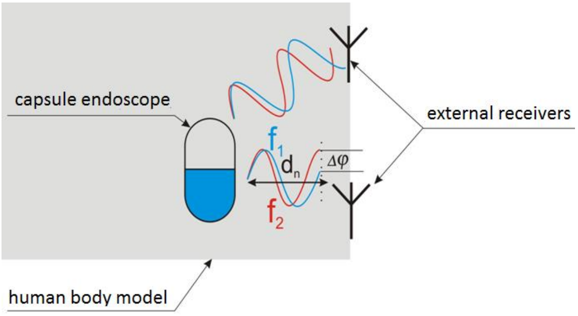

Fig. 1. Distance measurement with the use of PDOA method.

The state of the art methods [3][11][12] are able to localise the endoscope with the accuracy of 10-20 mm but their degree of complexity is much higher. Such methods require the utilization of multielement arrays of electromagnetic field sensors or signal sources. The method presented here allows its simple implementation. Compared to the method that uses the magnetic field tracking it has simple measurement setup and does not suffer for interferences between magnetic field sources and the influence of magnetic noise when the capsule battery need to be charged in the wireless inductive process.

The methods known from literature use information on human body structure for path loss model and for the capsule movement model. They utilize multi-path propagation model to estimate the parameters of signal that arrives from capsule during its movement [9]. For this relatively complex model of propagation the parameters of internal organ geometry should be well defined. Having this, the accuracy of 40-50 mm can be achieved. Unfortunately this models are sensitive for the different body structure of the patients. Proposed method, compared to other techniques based on phase analysis[10] does not require detailed body examination with NMR scanning to obtain information on its internal structure which is expensive and difficult to implement. Proposed adaptive model of body can be used instead, to obtain capsule localization also in 3D space.

III. METHODS

The proposed algorithm uses simplified homogenous model to approximate the velocity of wave propagation in the human body. It has electric permittivity that is automatically adjusted for each endoscope position. This mechanism was introduced to improve the localization accuracy in relation to the algorithm that was initially using the fixed value of the material properties. The input data in the presented algorithm are the coordinates of the receiving antennas located on the human body, the phase difference of the received signals and the initial value of electric permittivity of the simplified body model. The last value is automatically adjusted in each capsule position.

In the first part of the algorithm, basing on the phase difference of the received signals with formula 1 [13], the distances d_n between the capsule and receiving antennas located on the human body are calculated for each on n antennas:

$$d_n = \frac{c}{2 * \pi * \sqrt{\varepsilon}} * \frac{\Delta\varphi_n}{\Delta f} \tag{1}$$

d_n - distance of the capsule from the *N-th* antenna placed on the human body,

c - speed of light in a vacuum,

ε_r - model permittivity,

$\Delta\varphi_n$- phase difference of the received signals sent on two frequencies$f_1$andf_2,

Δf –difference between frequency $f_1$and f_2.

The estimated distances are only roughly approximated because they were calculated using homogenous human body model with one value of permittivity. Those values are affected by an error that results from the difference between a complex, in-body propagation environment and the assumed propagation in homogenous object. In the real object such effects like e.g. differences of tissues permittivity and wave reflection between tissues with different electrical parameters affects the signal phase in the receiver.

In the next step of the localization procedure, the Gauss-Newton algorithm that implements non-linear least squares method is used to estimate the geometric coordinates of the capsule. In this method we are looking for such values of u, v and w that minimize the sum of squares of residuals r_n that are, the values that minimize the function S, given by formula 2:

$$S = \sum_{n=1}^{N} r_n^2 \tag{2}$$

N - number of receiving antennas placed on the body,

$$r_n = d_n - \sqrt{(x-u_n)^2 + (y-v_n)^2 + (z-w_n)^2},$$

x, y, z - capsule coordinates,

u_n, v_n, w_n - coordinates of antennas placed on the body.

Due to the above mentioned propagation effects in human body, the global minimum of function (2) cannot be determined for the initially assumed value of model permittivity. In general case, for the phase differences recorded for the real (multi-tissue) case there is no suitable solution that would fit to the adopted model. In the proposed algorithm, for the best approximation of the desired endoscope position, the value of error function err_i (3) is calculated for the estimated position. This value is the mean square distance between the last two approximations of the capsule position, and it is calculated for each iteration (i) of Gauss-Newton algorithm until err_i is less than tolerance which is equal to the antenna size (20 mm) or the maximum number of iteration is reached.

$$err_i = \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2 + (z_i - z_{i-1})^2} \quad (3)$$

err_i - error of the i-th iteration of the least squares method,

x_i, y_i, z_i - capsule coordinates estimated in the $_i$-th iteration of the least squares algorithm, where $0<i<50$.

For the heterogeneous model for the average value of the permittivity equals to 52convergence condition is often not met. That is why in the last step, the algorithm is searching for such value of the electric permittivity that will minimize the error function (3), to achieve tolerance $tol<=20$ mm. In such case, the convergence condition of the Gauss-Newton algorithm will be achieved for the estimated distances between the capsule and the receiving antennas. For this purpose, the *fminbnd* function built-in in the Matlab environment was used, which adjusts permittivity of the model in the range of 30-80 to minimize the error described by equation 3. This function uses a hybrid method that switches between golden-section search and parabolic interpolation.

Figure 2 presents the algorithm for capsule tracking inside human body. In the first step the process of initialization is performed. At this stage the starting position of the capsule is defined at beginning of the digestive track and permittivity is set to average value for human tissues ε_r=52. Then, capsule localization is estimated using Gauss-Newton algorithm and adaptive human body model. Estimation algorithm is repeated until convergence condition is achieved. The maximum number of repetitions was set at 50 to avoid program deadlock. It may occur because proposed simplification of the human body makes that estimated distances (d_1-d_N) are affected by an error which depends on the degree of tissues properties variability in a given position. In this case, the estimates for which the smallest value of the error function (3) is obtained are selected.

When a new phase difference measurement of the received signals is performed, it is possible to determine a new position of the capsule. The final location result for each capsule position practically does not depend on the initial position, but reduces the number of algorithm steps as long as the convergence condition is achievable for the input data. Therefore to speed up the estimation process, the permittivity and the starting point are updated with the previously estimated permittivity value and capsule position. If the convergence condition for Gauss-Newton algorithm is not achieved this step is omitted and for new estimation previously estimated permittivity and initial positions are used to not propagate the error on next positions.

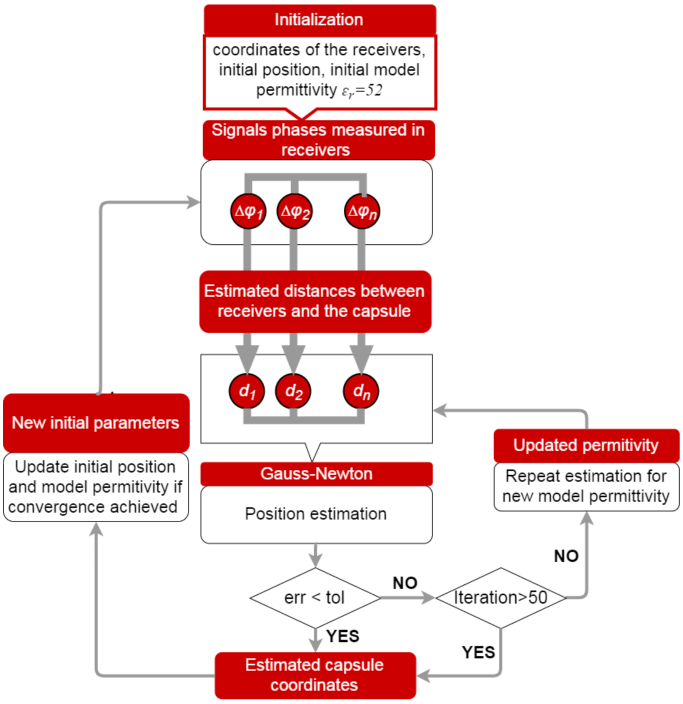

Fig. 2. Localization algorithm

IV. RESULTS

The localization algorithm proposed in this paper allows to determine the position of the endoscopic capsule in three-dimensional space. At this stage of the research it was assumed that the algorithm will be verified with computer simulations of signal phase-shift between transmitting endoscope antenna and receiving antennas located on body. The results of simulations obtained with heterogeneous model available in RemcomXFdtd software will be treated as the result of experiment with human body.

At this stage of our research, that is focused on the localization algorithm implementation, the numerical simulations for the simplified case were performed. To verify the proposed algorithm we did not investigate on the particular antenna design that should be used in this system. Instead, the simple half-wave dipole matched to work at 400 MHz in a medium with an electric permeability ε_r = 52 were utilized. The simulations were carried out in a heterogeneous environment, which is the human body. As the endoscopic capsules utilize the MICS (*Medical Implant Communication System*) band for data transmission in the frequency range from 401 to 406 MHz [14], in the simulations two sine-wave signals with a frequency of 403 MHz and 406 MHz were used. Simulations were performed using NMR Hershey human body model with a 5 mm voxel size, that is available in XFdtdRemcom simulation package [15]. This software implements finite difference time domain method for electromagnetic simulations.

The algorithm was verified on the basis of simulation data obtained for two human body models shown in Figure 3. In each case, the location of the signal source (endoscopic capsule) was determined in three-dimensional coordination system. The algorithm uses a homogeneous model of the human body to estimate the geometric coordinates of the endoscope. Therefore, in order to estimate the error introduced by the adopted simplification, it was decided to carry out simulations using two body models: a homogeneous model, that preserves the shape of the human body and secondly the heterogeneous model that keeps both the shape of body and electrical parameters of individual body tissues. In the case of a homogeneous model, the relative electric permeability $\varepsilon_r = 52$ and the specific electrical conductivity $\sigma = 1.8$ S/m [16] were assumed.

Simulations were performed for a dipole antenna placed vertically inside the model and receiving antennas located outside, as shown in figure 3. Human tissues surrounding the endoscope capsule are characterized not only by high dielectric permittivity but also by a high loss factor. This causes strong wave reflection and refraction especially at the interface between body and the air. In consequence phase of the received signal is significantly affected [17]. To minimize this effect external receivers were placed as close as possible to the numerical model of the human body. This cause the effect of antenna impedance detuning, however in the case of external antennas where there is no limitation to its dimensions, this effect can be compensatedby changing the antenna dimensions [18]. It was done at the antenna preparation stage where antenna was designed to be matched to operate in 400 MHz bandwidth when it is located near the human body.

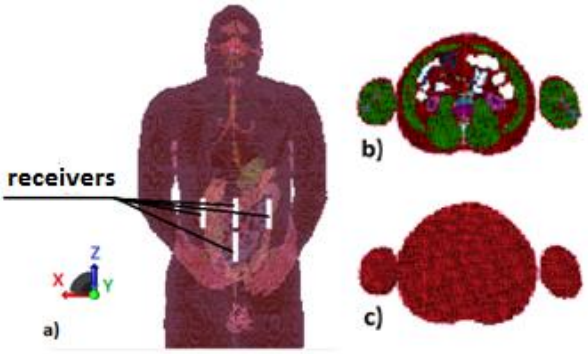

Fig. 3. Numerical model of the human body used in simulations. a)-arrangement of the receiving antennas relative to the model, b)-cross section of the heterogeneous model at the height of the receiving antennas, c) cross-section of the homogeneous model at the height of the receiving antennas

In order to define the proper placement of the receiving antennas on human body, a simulation was carried out in which the transmitting antenna was placed inside a heterogeneous human body model and the receiving antennas were located in various different places outside. Antenna arrangement is presented in the cross section of the model in Fig. 4. Based on the simulation results the distances between the transmitter and receiving antennas were determined with formula 1 where electric permittivity $\varepsilon_r = 20$ was assumed. This value was experimentally selected to minimize the error of the estimated distance for the antenna *A1*. Table 1 shows the results of distance estimation, which shows that the best accuracy was obtained for the receiving antennas placed on the torso at the front. For the antenna located at the back, that was placed at the distance of 140 mm, the estimated value of distance was 80 mm. For this reason, further numerical tests were made with receiving antenna configuration as shown on the Fig. 3.

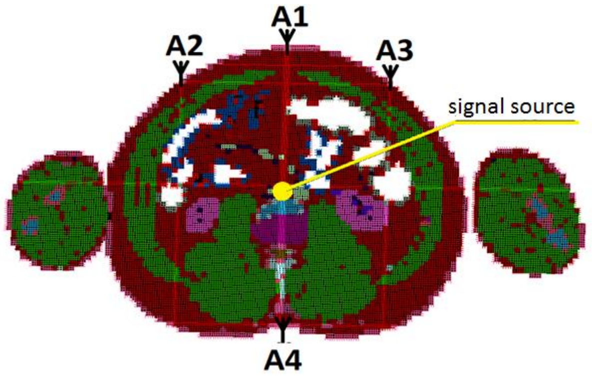

Fig. 4 Cross-section of a heterogeneous model with marked antennas used to evaluate the antenna arrangement on the estimated distance to the endoscopic capsule.

TABLE I
THE IMPACT OF RECEIVING ANTENNA PLACEMENT ON THE ESTIMATED DISTANCE TO THE ENDOSCOPIC CAPSULE

Antenna	*Actual distance [mm]*	*Estimated distance [mm]*	*Error[mm]*
A1	140	140	0
A2	140	136	4
A3	140	126	14
A4	140	80	60

A. Localization algorithm accuracy

The location algorithm was evaluated on the basis of data obtained from simulations in the XfdtdRemcom program [15] for a set of predefined positions of the transmitting antenna. As the initial position of the capsule in the localization algorithm, the origin of the coordinate system according to the Fig. 5 was adopted. The transmitter localization was investigated in lower part of digestive system. Its was changed within the human digestive system in the range $x = \pm$ 100 mm, $y = \pm$ 80 mm, $z = \pm$ 150 mm assuming the origin of the coordinate system according to figure 5. The dimensions given in the figure are: l_x = 330 mm, l_y = 290 mm, l_z = 650 mm. Next positions of the transmitter were randomly changed in the range from 1 mm to 20 mm for *Z* axis, and from -20 mm to 20 mm for *X* and *Y* axis.

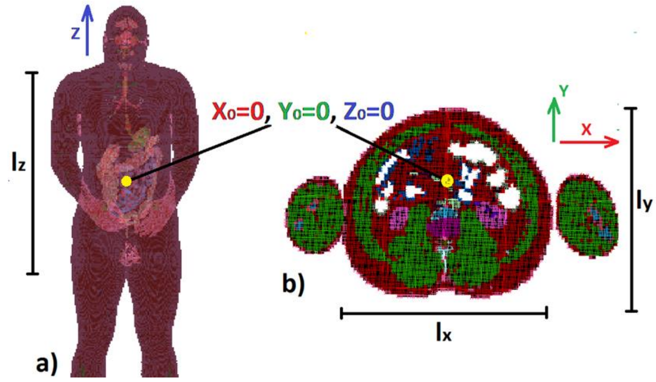

Fig. 5 Numerical model used in simulations: a – front view, b – cross-section in *XY* plane for *z=z0*.

Table II summarizes the results of the position estimation of the endoscopic capsule placed in two different body models (homogeneous and heterogeneous). For these models, two variants of the localization algorithm were compared: with a constant ε_r = 52, and with an adaptive ε_r in the range from 20 to 70. Localization error was defined as the mean square distance between the actual and the estimated position of the transmitting antenna. As a measure of the algorithm accuracy the smallest, the largest and average values of localization error were compared. In addition, the localization error was compared for each geometric coordinate. The results presented in the table 2 show the minimum, maximum and average error for a series of 30 positions of the endoscopic capsule.

The localization algorithm with the adaptive model of the human body improved the localization accuracy by around 12 mm (15 %) compared to the algorithm which implements the model with constant electric permittivity. Analyzing the obtained results for each coordinate separately, the proposed solution improves localization accuracy mainly for the Y and Z axes. For the X axis, the average localization error for a heterogeneous model is comparable to the size of the endoscopic capsule, so it can be assumed that it is at an acceptable level. The observed difference in accuracy for each coordinate could result from the location of the receiving antennas. This is due to the fact that the position of the endoscopic capsule with the use of presented algorithm can be estimated with the resolution comparable to the transmitter antenna, when the dielectric permittivity of the tissues is known. The smallest localization error was observed for such transmitter position in which it was located more or less at the height of the receivers (z = 0). Moreover, by introducing adaptive model in localization algorithm the convergence condition of Gauss-Newton method was achieved in about 95% cases. For comparison for an algorithm with a constant permittivity it was about 70 %.

TABLE II
OCATION ACCURACY FOR VARIOUS MODELS AND THE PRESENTED ALGORITHM

	Minimum error [mm]	Maximum error [mm]	Average error[mm]
Homogeneous human body model – constant model permittivity ε_r=52			
Mean square error	5	25	15
Error for X	0	10	7
Error forY	0	18	10
Error forZ	0	20	10
Heterogeneous human body model – constant model permittivity ε_r=52			
Mean square error	50	107	71
Error forX	2	23	11
Error forY	5	75	51
Error for Z	2	76	45
Heterogeneous human body model –adaptive model permittivity ε_r			
Mean square error	25	81	59
Error forX	2	23	10
Error forY	2	72	40
Error forZ	5	69	37

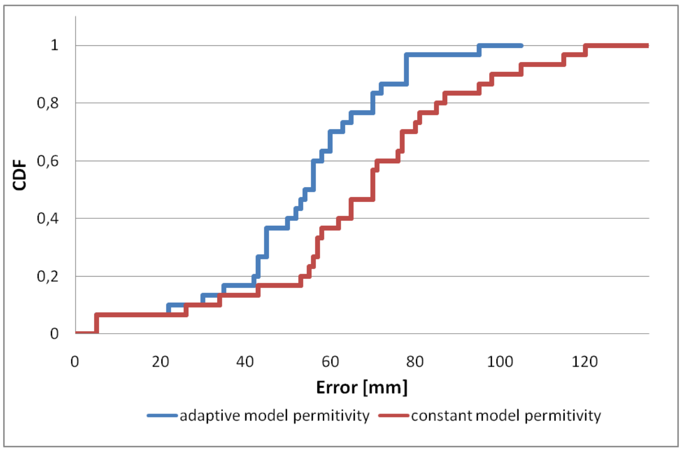

Fig. 6 CDF of localization error

B. The impact of the signals frequency difference on localization accuracy

In the proposed algorithm, the maximum value of phase difference of the received signals should be less than 180°, because it allows for unambiguous transformation of phase to the distance. In the previous section, the proposed algorithm was verified for signals within MICS frequency band where the difference between frequencies amounts to 3 MHz.Assuming that distance between transmitter and receiver can be up to 50 cm and the average permeability is 52, the maximum measured phase difference will be around 13°. Selecting the signal frequency in accordance with the specification for medical devices, requires then a high resolution and precision of measuring the phase difference in the receivers that can be difficult to achieve in the real system that may suffer from noise. By increasing the maximum value of the phase difference, it can be expected that the accuracy of the phase difference measurements will be grater what will result with improved accuracy of the localization. In order to minimize the impact of the receiving antennas arrangement on the localization accuracy, the analysis was carried out for the position of the transmitter, for which the previously studied localization error was the smallest (x=0, y=0, z=0). The simulation was carried out for 7 values of frequency $f_2$in the range of 406 - 443 MHz while the frequency f_1 was constant and amounted to 403 MHz for each case.

The figure 6 presents the impact of the frequency difference on the localization accuracy. The results were obtained with the use of the proposed algorithm with the adaptive human body model. Increasing the frequency of the second signal the maximum mean square error was reduced by around 28 mm (35%). Average and minimum mean square error value also shown improvement, but it is less than 10 mm. In the case of data obtained as a result of computer simulations, this problem certainly has a smaller impact on the localization error than it would be in the case of measurements where receiver noise also impacts accuracy. Although the increase of frequency f_2 gives an improvement, in the case of a real system it should be carefully selected due to possible interferences especially in the 434 MHz band.

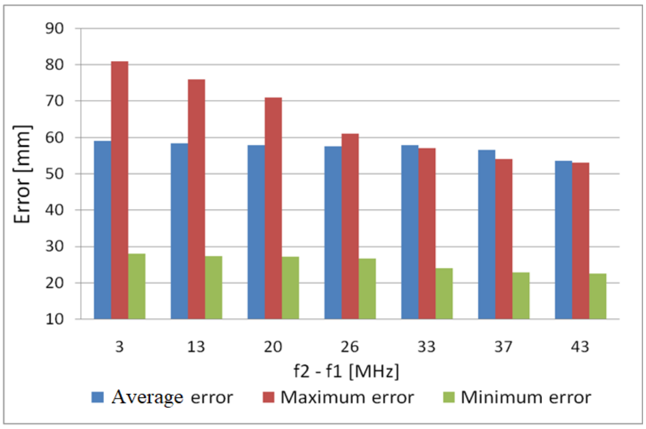

Fig. 7 Impact of frequency difference between transmitted signals on localization accuracy

C. *The impact of the transmitting antenna orientation on localization accuracy*

Endoscope capsule may rotate in digestive track. In consequence transmitting antenna in which the endoscopic capsule is equipped may change its orientation in relation to the receiving antennas.

To analyze the effect of antenna rotation, the simulations were carried out for the position of the transmitter, for which the localization error studied in subchapter *A* was the smallest (x=0, y=0, z=0).Antenna rotation was investigated in planes *ZX* and *ZY* changing the α and β angles in the range 0-90º according to three scenarios: first where α was changed β was 0, second where β was changed the α was 0 and third where both α and β were changed. Since dipole antenna has omnidirectional radiation pattern in the plane perpendicular to the wire axis (*XY* plane) analysis in this plane was omitted. Figure 2 presents the range of the α and β angle in relation to NMR Hershey body model.

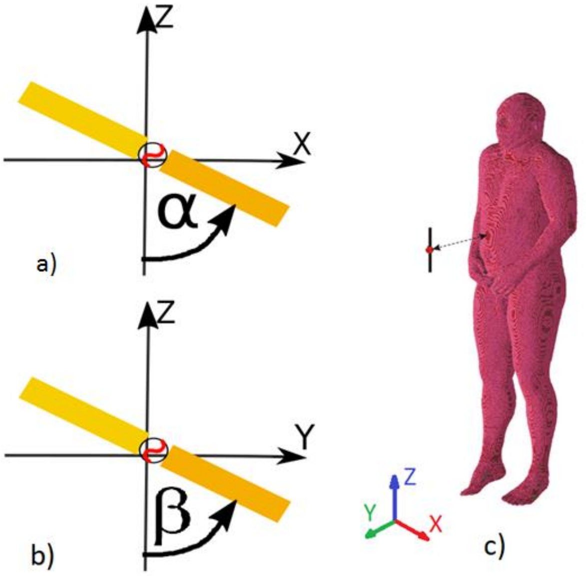

Fig. 8 The numerical experiment with NMR Hershey model: a – dipole antenna rotation angle in ZX plane, b – dipole antenna rotation angle in ZY plane, c - antenna location height in the model in NMR Hershey model

Table III, IV and V summarize the results of the analysis of antenna rotation influence on localization accuracy. The localization error increases to c.a. 20 mm when the angle is changed in both planes in range from 30º to 60 º. When the angle is increased to 90 º the error increases up to 43 mm especially in *ZY* plane. It is because in this case the plane in which the receiving antennas are located is perpendicular to the transmitter wire axis and in this direction dipole gain is falling to 0.

TABLE III
THE IMPACT OF TRANSMITTING ANTENNA POLARIZATION CHANGE IN *ZY* PLANE ON LOCALIZATION ACCURACY

α [º]	Error for X [mm]	Error for Y [mm]	Error for Z [mm]	Mean square error[mm]
0	2	27	1	28
30	5	38	6	40
45	4	36	2	38
60	10	31	7	35
90	4	60	5	61

TABLE IV
THE IMPACT OF TRANSMITTING ANTENNA POLARIZATION CHANGE IN *ZX* PLANE ON LOCALIZATION ACCURACY

β [º]	*Error for X [mm]*	*Error for Y [mm]*	*Error for Z [mm]*	*Mean square error[mm]*
0	2	27	1	28
30	12	34	8	37
45	8	26	15	31
60	21	30	4	37
90	11	61	18	71

TABLE V
THE IMPACT OF TRANSMITTING ANTENNA POLARIZATION CHANGE IN ZX AND ZY PLANE ON LOCALIZATION ACCURACY

α, β [º]	*Error for X [mm]*	*Error for Y [mm]*	*Error for Z [mm]*	*Mean square error[mm]*
0	2	27	1	28
30	13	40	28	48
45	12	24,5	5,5	28
60	15	42	7	45
90	11	51	2	55

CONCLUSION

The article presents the algorithm for locating the endoscopic capsules in three-dimensional space, basing on the phase difference of received signals. The algorithm uses the adaptive simplified model of the human body, which allowed to improve the localization accuracy when the dielectric permeability of the tissues, through which the radio wave propagates is unknown. The algorithm accuracy was evaluated on the basis of the simulation results obtained with the use of finite difference in the time domain method.

In the considered case, the minimum number of antennas was used to determine the position of the object in three-dimensional space. Their proposed arrangement allowed to minimize the impact of different human body structure on the localization result. It was shown that the position of receiving antenna on body surface has the impact on the system accuracy. In further work on the presented system, the placement of receiving antennas and their number will be studied.

Increasing the frequency difference between signals emitted by the endoscope capsule the maximum localization error has been reduced. Simulation data are not affected by receiver noise therefore this parameter does not significantly improve obtained results. This aspect should be evaluated again when the algorithm will be tested with the use of physical phantoms and receivers.

Changing the orientation of the transmitting antenna relative to external antennas affects the result of localization. This is due to the radiation pattern of the half-wave dipole antenna used in experiment. To eliminate this effect, it is planned to apply the antenna diversity technique in the receivers.

The simulation experiment using a heterogeneous body model showed that the localization algorithm with adaptive homogeneous human body model allows to improve localization accuracy of around 12 mm (15%) compared to the algorithm with constant electrical permeability. In order to obtain greater accuracy, it is planned to use more complex propagation models for the body. It is also planned to verify the algorithm with measurements data obtained with human body phantoms.

In the proposed algorithm the localization error is still bigger than in case of method which uses NMR scans of the patient's body[10], that can reach accuracy of 2 cm. However, the advantage of the proposed algorithm with adaptive human body model is that it can be used for patient without the a priori knowledge of exact internal body structure. This is of great importance in the case of transmitter located inside the intestines because they have variable arrangement in the peritoneal cavity. Moreover the much simpler transmitter that can be used in this method that is important in the case of miniature capsules with limited power resources.

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