Location Accuracy Estimates of an Ingested Wireless Endoscopy Capsule based on an RSSI Cost Function

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Abstract—**The accurate location of an internal radio transmitter is important for long-term patient monitoring. An inverse solution for the surface field attenuation-based algorithm provides a simple position estimation but is degraded by noise and movement artefacts. Using the minimum cost function between the predicted and experimentally received signal strength indicators (RSSI) for four skin-surface receivers, the localization accuracy within 10 mm was achieved even with movement and external Gaussian noise. The relationship between RMSE value of each coordinate component in 3D under various noise levels provides a location accuracy estimate.**

Keywords—radio pill; localization accuracy; cost function; optimization; wireless capsule endoscopy.

I. INTRODUCTION

Wireless technologies are used for many medical applications. One example is wireless capsule endoscopy (WCE), which involves the patient swallowing a miniaturized capsule that has a camera to record the condition of their gastro-intestinal tract during the passage through the gut, and a radio-transmitter to transfer this data for further analysis [1]. Accurate localization of this capsule is of great importance for a correct diagnosis and precise treatment. Radiofrequency signal analysis is a common method reported for wireless endoscopy localization and techniques such as time-of-flight, angle-of-arrival and received signal strength indicator (RSSI) are under active investigation [2]. In this paper, we further explore an RSSI-based method, as it does not require any additional ingestible capsule hardware or firmware, or precise timing of multiple skin sensors.

Considering that human body is a lossy medium, radio signals are highly attenuated, which means that the relationship between the power and the distance is not linear. This study is focused on the development of an inverse algorithm that provides an automatic comparison of experimentally acquired intensity values at four spaced locations on the skin, with the corresponding values of an input model to determine the position of a transmitter inside the torso. The input model used for this purpose was developed at the previous stage of our research based on an attenuation algorithm, which takes into account specific frequency dependent electromagnetic characteristics of the media, and allows modelling of the surface field intensity around the torso [3].

This paper describes a solution for a corresponding optimization problem using sequential sampling for cost function minimization. In particular, the position estimate root-mean-square error (RMSE) in each coordinate component of the location was calculated, and its relationship with additive RSSI noise was described. This has not been reported previously (to the best of our knowledge).

II. INVERSE MODEL SOLUTION

A. Problem formulation

Since the correlation between the received intensity and the distance between the receiver (Rx) and the transmitter (Tx) is not linear, the dipole location was estimated by finding the most appropriate Rx and Tx model in accordance with the correct coordinates of the pill. The input is the intensity value of the surface radiation at a particular point for a given location of the ingested transmitter. The objective function, or cost function (*CF*), is the difference of the intensities predicted using a surface electric field attenuation based algorithm [3] and the measured field intensity values. The minimum *CF* value corresponds to the best match of the modelled and measured surface radiation intensities for the unknown input values and the real position of the pill. The cost function is defined as follows:

$$CF(M) = \sum_{n=1}^{N} [P_2(n) - P_1(M,n)]^2, \qquad (1)$$

where N is the number of receiving sensors, P_2 is the intensity of the field measured by the surface sensors placed at N different locations, P_1 is the intensity of the field modelled prior at the same N different surface locations; and M is the number of all possible dipole locations (Tx) inside the model (2025810 values according to the model used). Every Tx location and orientation gives a different intensity map. Given the large dynamic range (over 100 dB) of possible signal intensities, the calculations (1) are based on dBm values.

The minimum *CF* was determined using exhaustive search or sequential sampling and the cost function was calculated for all possible pill locations in a 3D model based on an elliptical cylinder. The model dimensions created in Matlab® were 0.15 m for the anterior-posterior radius, and 0.2 m for the medio-lateral radius, the height of the model was 0.4 m. Using the frequency 433 MHz, the relative permittivity of the soft tissue medium was 62, and the conductivity was 0.87 S/m. This follows previous forward modelling results obtained in [3].

The Tx resolution was defined by a step size of 0.005 m in the horizontal plane (*x* and *y* directions) and 0.01 m in the vertical plane (*z*-direction). This resulted in a [3×202581] intensity matrix covering all possible positions of the dipole inside the model. Four receivers ($N = 4$) were chosen for the dipole position estimation in 3D model, since an estimate of the three unknowns (the *x*, *y*, and *z* values for the pill) is required.

For this stage of the investigation, the focus has been on the location estimation accuracy. The orientation of the dipole was fixed as vertical ensuring that no nulls are found on the skin surface. The influence of the pill dipole orientation will be investigated in future work.

B. *Simulation results*

In order to represent a more realistic scenario, the four surface field intensity values in dBm were adjusted by adding Gaussian noise (with a variance of 5 dBm). This accounts for uncertainties caused by extraneous local transmitters, natural body movement (breathing and other muscle activity) and the coupling of the receivers to the skin surface. Furthermore, inhomogeneity of the real human abdomen region could be accounted by the considered noise level, since electromagnetic properties of the soft tissues in that region are very similar.

The RMSE was $x = 0.012$ m; $y = 0.0088$ m and $z = 0.0359$ m for 50 simulations using a randomly selected Tx location. Figure 1 shows the calculated Tx localization (red dots) for 50 randomly determined Tx positions (blue circles) within the model.

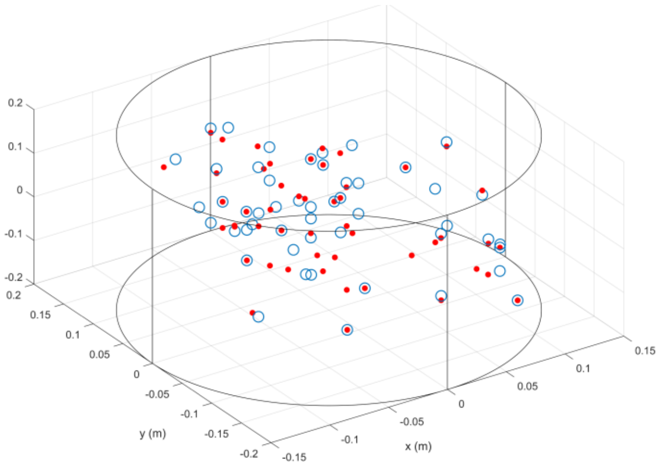

Fig. 1. 3D representation of the localization errors within the elliptical model of the human torso for 50 randomly selected Tx locations. (● is the estimated location, and ○ is the actual location).

The effect of normally distributed random noise levels on the minimum value of the cost function in these simulations, allowed an estimation of the relationship between the noise level and the accuracy of the localization for each coordinate component. The RMSE (corresponding to the positional error) and the noise level are shown in Fig. 2. The position of the dipole for these simulations was assigned randomly within the model torso volume (less 0.05 m from the surface), and it corresponds to the possible anatomical locations in the GI tract.

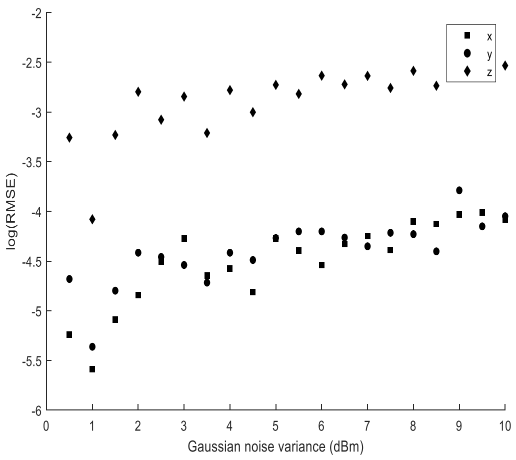

Fig. 2. RMSE values for each coordinate component x (■); y (●); z (♦) with additive Gaussian noise. The RMSE values for z are the highest as the step function in the model is larger. The 3D localization RMSE varies from 0 to 0.08 m for the highest noise. Note that for no noise, the estimation is exact as the steps sizes are identical for the location and estimation.

III. CONCLUSION

The localization of the dipole transmitter was achieved by sequentially sampling all possible locations and finding the minimum cost function within the proposed inverse solution model. The RMSE for each individual coordinate component was $x = 0.012$ m; $y = 0.0088$ m and $z = 0.0359$ m with the noise level of ±5 dB. The positional accuracy decreased with increased Gaussian noise.

For the highest noise range (variance of 10 dBm), the RMSE was found in the range from 0.01 to 0.04 m. The lowest considered noise range (variance of 0.5 dBm) resulted in the RMSE ranging from 0.001 m to 0.005 m. The algorithm presented in this paper can provide a valuable tool for the estimation of the influence of the noise on the localization accuracy.

Future work will focus at further validation of the localization algorithm for the ingested transmitter based on uniform attenuation, including the expansion of the inverse solution for dipole orientation using more advanced optimization techniques.

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