Novel Joint TOA/RSSI-Based WCE Location Tracking Method without Prior Knowledge of Biological Human Body Tissues

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***Abstract*— This paper proposes a novel joint time of arrival (TOA)/received signal strength indicator (RSSI)-based wireless capsule endoscope (WCE) location tracking method without prior knowledge of biological human tissues. Generally, TOA-based localization can achieve much higher localization accuracy than other radio frequency-based localization techniques, whereas wireless signals transmitted from a WCE pass through various kinds of human body tissues, as a result, the propagation velocity inside a human body should be different from one in free space. Because the variation of propagation velocity is mainly affected by the relative permittivity of human body tissues, instead of pre-measurement for the relative permittivity in advance, we simultaneously estimate not only the WCE location but also the relative permittivity information. For this purpose, this paper first derives the relative permittivity estimation model with measured RSSI information. Then, we pay attention to a particle filter algorithm with the TOA-based localization and the RSSI-based relative permittivity estimation. Our computer simulation results demonstrates that the proposed tracking methods with the particle filter can accomplish an excellent localization accuracy of around 2 mm without prior information of the relative permittivity of the human body tissues.**

I. INTRODUCTION

In recent years, wireless body area networks (BANs) has attracted lots of attention with respect to medical and healthcare applications [1]. Wireless BANs realizes novel promising medical and healthcare applications such as wireless capsule endoscopy. In wireless capsule endoscopy systems, the location information of the wireless capsule endoscope (WCE) can help detecting diagnose gastrointestinal (GI) conditions and assisting the physicians for follow-up interventions. However, since a WCE moves inside a human body, nobody knows its location in advance. Therefore, in the capsule endoscopy systems, it is significant to estimate and track the WCE location.

Various kinds of WCE localization methods have been so far proposed [2]–[5]. For example, localization technologies include ultrasound, radio frequency (RF)-based techniques [2]–[4], magnetic tracking [5]. In these technologies, the localization with RF signals are advantageous in terms of relatively low cost for implementation due to requiring no specific device. In this paper, we pay attention to time of arrival (TOA)-based location estimation because it can achieve much higher localization accuracy than other RF-based location estimation.

However, whereas the propagation velocity in free space is always constant, the propagation velocity inside a human body should be different from one in free space because wireless signals transmitted from a WCE pass through various kinds of human tissues. Therefore, it is important to estimate the propagation velocity for accurately tracking the WCE location with the TOA technique. The variation of propagation velocity is mainly affected by the relative permittivity of human body tissues, so the propagation velocity can be estimated by using the relative permittivity information. In the related works, for example, in order to obtain the relative permittivity information, the literature [3] makes use of the images of inside of a human body, which are acquired beforehand from a magnetic resonance imaging (MRI) or computed tomography (CT) system. For considering the use in a reality, troublesome pre-measurement of the human body structure is unsuitable to the wireless capsule endoscopy systems. Therefore, in this paper, we simultaneously estimate not only the WCE location but also the relative permittivity, instead of pre-measurement for the relative permittivity information in advance.

For this purpose, this paper first derive the relative permittivity estimation model with measured RSSI information. Then, we focus on a particle filter tracking algorithm, which can improve the localization accuracy to take the behavioral nature of WCE in consideration [4], and introduce the TOA-based localization and the RSSI-based relative permittivity estimation into the particle filter tracking algorithm. Finally, we evaluate the performance for the proposed joint TOA/RSSI-based location tracking method by computer simulations, and compare the localization performance of the proposed method with those of the existing methods.

II. RELATIVE PERMITTIVITY ESTIMATION WITH MEASURED RSSI INFORMATION

A. System Model

We assume that a WCE is located inside a human body and M receivers are put onto the human body as shown in Fig. 1. The positions of receivers are known in advance and the WCE location is unknown, so the WCE location should be estimated by the known receiver location information. We define the three-dimensional locations of the WCE and the m-th receiver ($m = 1, \cdots, M$) as

$$\mathbf{r} = [x, y, z]^T \quad (1)$$

$$\mathbf{r}_m = [x_m, y_m, z_m]^T \quad (2)$$

where $(\cdot)^T$ indicates the transpose of $(\cdot)$. As for the transmitted wireless signal, we employ an ultra wideband-impulse radio (UWB-IR) pulse whose frequency band is assumed to

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3.4–4.8 GHz (UWB low-band). Note that the TOA τ can be detected by using calculation of the cross correlation between the transmitted and received signals, and the RSSI E is determined as the peak received electric field intensity of the received UWB-IR pulse. Furthermore, based on the measured TOA τ, the transceiver distance can be estimated as [1]

$$\hat{d}(\tau, \varepsilon_r) = \frac{c}{\mathrm{Re}\left[\sqrt{\varepsilon_r - j\frac{\sigma}{\omega\varepsilon_0}}\right]}\tau \tag{3}$$

where c, ε_r, ε_0 and σ denote the speed of light, the relative permittivity of a human body, the relative permittivity in free space and the conductivity of a human body, respectively. We note that $\hat{(\cdot)}$ means the estimated value of $(\cdot)$. Since we use the UWB low-band signal in this paper, (i.e., ε_r is sufficiently larger than $\sigma/\omega\varepsilon_0$), Eq. (3) can be approximated as

$$\hat{d}(\tau, \varepsilon_r) \approx \frac{c}{\sqrt{\varepsilon_r}}\tau. \tag{4}$$

The above equation means that estimation of the transceiver distance requires both the TOA τ and the relative permittivity ε_r.

B. Proposed Relative Permittivity Estimation

From Eq. (4), for introducing the TOA technique into WCE location tracking, the relative permittivity ε_r should be also required. In this paper, we estimate ε_r based on the RSSI information (RSSI means E as defined below). Because a human body is actually composed of various kinds of biological tissues, several lossy dielectrics exist between the transmitter (WCE) and the receiver. For simplification of the estimation problem, this paper assumes that there is only one biological tissue between the WCE and the receiver, which has the electric constants (namely, the relative permittivity and conductivity) averaged over the several lossy dielectrics. In this case, assuming that the transmitted signal radiates in a spherical wave form, the received electric field intensity, that is, the RSSI E can be approximately expressed as [1]

$$E = f(\varepsilon_r) = \frac{1}{d}E_0 e^{-\alpha(\varepsilon_r)d} \tag{5}$$

$$\alpha(\varepsilon_r) = \omega\sqrt{\mu_0\varepsilon_0\varepsilon_r}\ \mathrm{Im}\left[\sqrt{1 - j\frac{\sigma}{\omega\varepsilon_0\varepsilon_r}}\right] \tag{6}$$

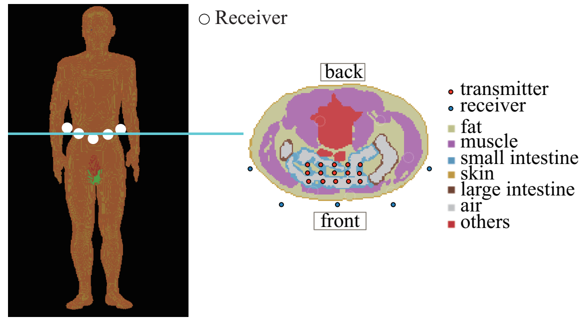
where E_0, μ_0 and ω mean the electric field intensity of the transmitted signal on the body surface, the magnetic permeability in free space, and the angular frequency, respectively. Consequently, the relative permittivity can be estimated as

$$\hat{\varepsilon}_r = f^{-1}(E) \tag{7}$$

where $f^{-1}(\cdot)$ indicates the inverse function of $f(\cdot)$ in Eq. (5).

C. Validation of Relative Permittivity Estimation Model

In order to validate the proposed relative permittivity estimation model, we employed finite difference time domain (FDTD) simulations. The employed anatomically human body model, which was developed by National Institute of Information and Communication Technology, Japan [6], is shown in Fig. 1. The human body model is 1.73 m tall and 65 kg weight, and is composed of 51 kinds of biological tissues with a spatial resolution of 2 mm. The transmit antenna of the WCE was assumed inside the small intestine of the human body, and the receive half-wavelength dipole antennas were placed at five locations on the body surface. In the FDTD simulations, a 2-mm long dipole as the transmit antenna was moved to have 15 locations inside the small intestine as shown in Fig. 1.



(a) Front view (b) Top view

Fig. 1. System model for WCE localization.

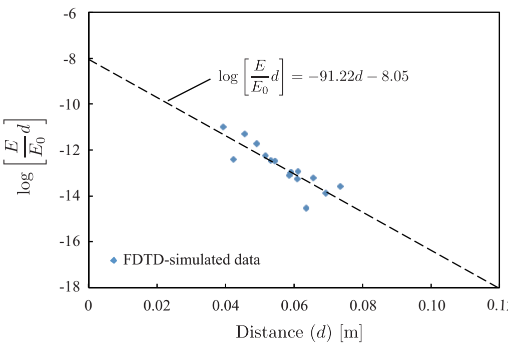


Fig. 2. Validation results for relative permittivity estimation model.

Fig. 2 shows the FDTD-simulated results for the validation of the relative permittivity estimation model. This figure indicates that the estimation of the relative permittivity actually requires E/E_0, which can be obtained from the square root of the ratio of the receive to transmit signal powers. From these results, the relationship between the relative permittivity and the received electric field intensity is well expressed by Eq. (5) because the correlation coefficient between the FDTD-simulated data and the data obtained by the approximated line is 0.702. We would like to note that, whereas the proposed relative permittivity estimation assumes the only one average biological tissue, good estimation accuracy of the relative permittivity based on the received electric field intensity is expected to be accomplished.

III. Proposed Joint TOA/RSSI-Based Location Tracking with Particle Filter

The proposed particle filter tracking algorithm with the joint TOA/RSSI-based localization repeats the following four steps in an iterative manner.

A. Prediction Step

The state of each particle is determined by state transition model of the WCE location. This paper assumes the following random way point model as the realistic transition model [4]:

$$\begin{aligned} \mathbf{r}_i[n] &= \mathbf{r}_i[n-1] + v_i[n]\mathbf{e}_i^k \Delta t && (8) \\ v_i[n] &\sim \mathcal{N}(\bar{v}, \sigma_v) && (9) \\ \mathbf{e}_i^k &= \frac{\mathbf{g}_i^k - \mathbf{g}_i^{k-1}}{|\mathbf{g}_i^k - \mathbf{g}_i^{k-1}|} && (10) \\ \mathbf{g}_i^k &\sim \begin{bmatrix} \mathcal{U}(0, LX) \\ \mathcal{U}(0, LY) \\ \mathcal{U}(0, LZ) \end{bmatrix} && (11) \end{aligned}$$

where $\mathbf{r}_i[n]$, $v_i[n]$, $\bar{v}$, σ_v, Δt and $\mathbf{g}_i^k$ represent the i-th particle location at the discrete-time index of n, the velocity of the i-th particle at the discrete-time index of n, the average velocity of the WCE moving, the standard deviation of the velocity of the WCE, the time interval of the location tracking and the k-th destination location vector of the i-th particle, respectively, and $\mathcal{N}(\mu, \sigma)$ and $\mathcal{U}(a, b)$ are the Gaussian distribution with mean μ and standard deviation σ, and the Uniform distribution between a and b, respectively. Furthermore, the particle state space has not only the particle location $\mathbf{r}_i[n]$ but also the relative permittivity information $\varepsilon_{m,i}$ for each receiver (the subscript r is dropped without loss of generality in this section).

B. Update Step

In the update step, the weight of each particle $\tilde{w}_i[n]$ at the time index of n is updated as in the following way:

$$\begin{aligned} \tilde{w}_i[n] &= w_i[n-1] \prod_{m=1}^{M} p(\tau_m, \hat{\varepsilon}_m | \mathbf{r}_i[n], \varepsilon_{m,i}) && (12) \\ w_i[n] &= \frac{\tilde{w}_i[n]}{\sum_{j=1}^{N_p} w_j[n]} && (13) \end{aligned}$$

where $w_i[n]$, N_p is the normalized weight of the i-th particle, the number of particles, respectively. Here, the subscript m means the index of the receiver (for example, τ_m is the TOA measured at the m-th receiver), and $\hat{\varepsilon}_m$ is the relative permittivity estimated by Eq. (7) with the RSSI measured at the m-th receiver. The probability density function (*pdf*) in Eq. (12) can be decomposed into

$$p(\tau_m, \hat{\varepsilon}_m | \mathbf{r}_i[n], \varepsilon_{m,i}) = p(\tau_m | \mathbf{r}_i[n], \varepsilon_{m,i}) p(E_m | \varepsilon_{m,i}). \quad (14)$$

Taking the sampling error of TOA measurement into consideration, the former term of Eq. (14) is given by [7]

$$p(\tau_m | \mathbf{r}_i[n], \varepsilon_{m,i}) = \frac{1}{\sqrt{2\pi}\sigma_s} \exp\left[-\frac{(\tau_m - \overline{\tau}_{m,i})^2}{2\sigma_s^2} \right] \quad (15)$$

$$\overline{\tau}_{m,i} = \frac{\sqrt{\varepsilon_{m,i}}}{c} |\mathbf{r}_i[n] - \mathbf{r}_m| . \quad (16)$$

On the other hand, the latter term of Eq. (14) is assumed as

$$p(\hat{\varepsilon}_m | \varepsilon_{m,i}) = \frac{1}{\sqrt{2\pi}\sigma_e} \exp\left[-\frac{(\hat{\varepsilon}_m - \varepsilon_{m,i})^2}{2\sigma_e^2} \right] \quad (17)$$

TABLE I
PARAMETERS OF COMPUTER SIMULATIONS

$LX \times LY \times LZ$	40cm×40cm×20cm
Resampling threshold β_{thr}	0.1
Δt	0.1 s
$\bar{v}$	0.05 cm/s
σ_v^2	0.005 $(\mathrm{cm/s})^2$
σ_s	62.5 ns

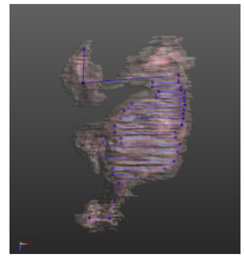


Fig. 3. Trajectory of WCE movement.

where σ_e represents the error standard deviation of the relative permittivity estimation. From the FDTD simulation results in the previous section, the correlation coefficient between the FDTD-simulated data and the *pdf* data obtained by Eq. (17) results in 0.8426, and σ_e of 9.7 is obtained.

C. Resampling Step

In the particle filter algorithm, it is necessary to remove the particles whose weights are relatively small and regenerate them. For this purpose, we define the effective parameter as $\beta_{eff} = 1/\sum_{i=1}^{N_p} w_i^2[n]$. Some particles with negligible weights are eliminated and regenerated as the copy of the particle with a relatively large weight.

D. Estimation Step

Finally, the estimated location is calculated as

$$\hat{\mathbf{r}}_{PF}[n] = \sum_{i=1}^{N_p} w_i[n] \mathbf{r}_i[n]. \quad (18)$$

IV. PERFORMANCE EVALUATION

A. Simulation Environment

In order to evaluate the performances of the proposed joint TOA/RSSI-based location tracking method, we performed computer simulations. In the computer simulations, we assumed that the WCE moves inside a small intestine according to the random way point model described in the previous section, and the destination location of the transition model was determined based on the small intestine of the anatomical human model in advance as shown in Fig. 3. We put 8 receivers at each vertex of the cuboid. Finally, the computer simulation parameters are summarized in Table I.

B. Results

Fig.4 shows the root mean square (RMS) location estimation error for the proposed location tracking method in the cases of the number of particles N_p of 100, 1,000 and 10,000. As can be seen from this figure, as the number of particles increases, we can improve the localization performance at

TABLE II

PERFORMANCE COMPARISON BETWEEN THE PROPOSED AND THE EXISTING METHODS

	Proposed	Fischer, 2004 [2]	Kawasaki, 2009 [3]	Ito, 2014 [4]
Localization technique	TOA/RSSI	RSSI	TOA	RSSI
Number of dimensions of estimated WCE location	3	1	2	3
Pre-measurement of model parameters (including relative permittivity information)	None	Required	Required	Required
Achievable RMS location estimation accuracy	2 mm	37.7 mm	10 mm	7 mm

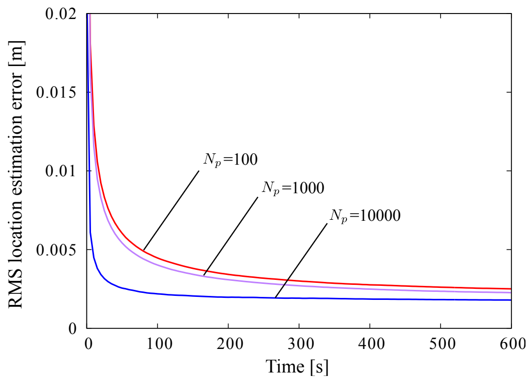


Fig. 4. RMS location estimation error for the proposed tracking method.

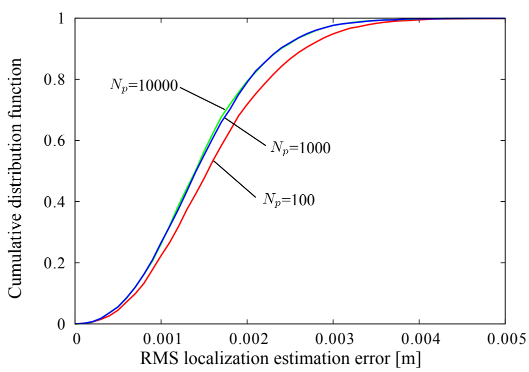


Fig. 5. *cdf* of location estimation error.

the sacrifice of computational complexity. In all the three cases, the localization performance of the proposed tracking method quickly converges to an excellent estimation accuracy. For example, when the number of particles is 10,000, the achievable RMS location estimation error is about 2 mm.

Then, Fig.5 shows the cumulative distribution function (*cdf*) on the location estimation error for the proposed tracking method. From Fig.5, the maximum location estimation error of the proposed tracking method is achieved within 4 mm. Furthermore, when the *cdf* of the location estimation error is 0.8, the proposed tracking method can accomplish the accuracy of around 2 mm in the case of the number of particles of 10,000.

Finally, let us compare the localization performance for the proposed location tracking with those for the existing methods. Table II summarizes the performance comparison between the proposed and the existing methods. It should be noted that, two compared methods (Kawasaki, 2009 [3] and Ito, 2014 [4]) in Table II also took inhomogeneous biological tissue structure into consideration to evaluate the localization accuracy, as that in this paper. This table indicates that only the proposed method does not require pre-measurement of model parameters including the relative permittivity information. Nevertheless, the proposed method can achieve the excellent accuracy of 2 mm, for example, as compared with the existing method of (Ito, 2014), the proposed tracking method can improve the RMS location estimation accuracy by around 70 %.

V. CONCLUSIONS

This paper has proposed a novel joint TOA/RSSI-based WCE location tracking method without pre-measurement of relative permittivity information. This paper has first derived the relative permittivity estimation model with measured RSSI information, and we then have introduced a particle filter algorithm into the TOA-based localization and the RSSI-based relative permittivity estimation. From our computer simulation results, the achievable RMS location estimation error of 2 mm has been confirmed. Furthermore, the proposed tracking methods can improve the estimation accuracy by around 70% as compared with the existing methods.

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