A Method for Improving the Wearability of Capsule Positioning System Using Particle Filter

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***Abstract*—Ingestible capsules with position tracking capabilities bring a significant advancement in the diagnosis and treatment of gastrointestinal disorders. However, the wearability of these capsule positioning systems is restricted by the weight and shape of the transmitter (Tx). To enhance the wearability and flexibility of the system, a novel positioning system using particle filter (PF) is proposed. By employing PF, the system can calculate the capsule's position in 3D space using only a belt-shaped Tx coil, paired with a single Rx coil and an inertial measurement unit (IMU). PF iteratively updates the estimated position based on the capsule movement and changes in mutual inductance (MI). The performance of PF with different noises is analysed. Simulation results show that the system has a 22.5 × 11.5 × 27 cm^3 field of view (FOV), a root mean square error (RMSE) of 13.89 mm under noise.**

Keywords—Capsule localization, Gastrointestinal tract, Ingestible capsules, Inertial navigation, Particle filter.

I. INTRODUCTION

Wireless ingestible capsules provide a valuable method for diagnosing and treating gastrointestinal disorders [1]. One key function of these devices is continuous monitoring of the gastrointestinal tract (GI). It improves the diagnosis accuracy of gastrointestinal motility disorders, such as gastroparesis, ileus, and constipation [2].

Current research on the localisation of capsules can be divided into two methods based on their working principles: Radio frequency (RF) techniques and magnetic field-based methods. RF techniques include the received signal strength (RSS), time of flight (ToF), direction of arrival (DoA), and radio frequency identification (RF-ID) [3],[4]. The accuracy of this method is affected by penetration depth and variations in body tissues. As RF signals pass through the body, different organs, bones and tissues exhibit varying permittivity, resulting in non-homogeneous signal absorption [3],[5].

Magnetic field-based methods have advantages over RF methods because of the homogeneous permeability of the human body to magnetic fields, which makes the system robust to the changing environment [6]. The positioning system with static magnetic fields uses Hall effect sensors to sense the magnetic field strength to position the capsule. These systems require a high-power supply or permanent magnets as the transmitter (Tx) to generate a strong magnetic field. The accuracy of the system is sensitive to the power supply level and environment magnetic field [2]. Tx array is a common solution to improve the accuracy and degree of freedom in the magnetic method [2],[7]. These systems use multiple Tx coils or sensors. However, the shape of the planar or three-dimensional (3D) Tx array has limited wearability, which requires complex equipment procedures or for patients to be kept within the effective range of the system. Moreover, the power consumption of Tx dictates whether it can be powered by a battery. Thus, weight, shape and power consumption constrain the wearability of the positioning system. A challenge for these types of devices is to improve their wearability while maintaining the positioning performance. For GI monitoring systems, their positioning accuracy requirement is in the sub-centimetre range as the average diameter of the small intestine is around 2.5 cm [1].

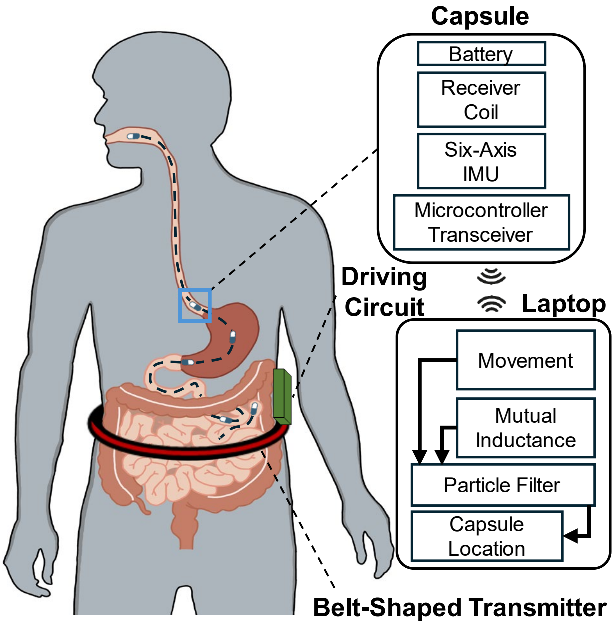

Fig. 1. The concept of proposed system architecture that consists of a belt-shaped transmitter, an ingestible capsule with six-axis IMU and microcontroller, and a laptop for data aquisition and position calculation.

In this paper, a particle filter (PF) is implemented for positioning. The PF requires only two measurements to estimate the position of the capsule in 3D space, eliminating the need for an array of Tx coils. This feature allows the proposed system to use only a single Tx coil, significantly reduce the weight and power consumption.

II. PARTICLE FILTER AND INERTIAL MEASUREMENT UNIT

PF is a statistical method that combines Monte Carlo random sampling with Bayesian filtering to approximate solutions for nonlinear state-space systems. The algorithm represents the posterior distribution of a stochastic process using a set of discrete, weighted particles in the state space [8]. PF requires two measurement inputs. The first is typically the control input or system dynamics, which represents the system's motion. The second is the observation or sensor data, which provides the current state. PF combines these measurements to update the probability distribution. Since the movement of the capsule cannot be directly measured after it is swallowed, an inertial measurement unit (IMU) is used to track its motion. In this work, each particle represents an estimated position of the capsule, and particle weights are

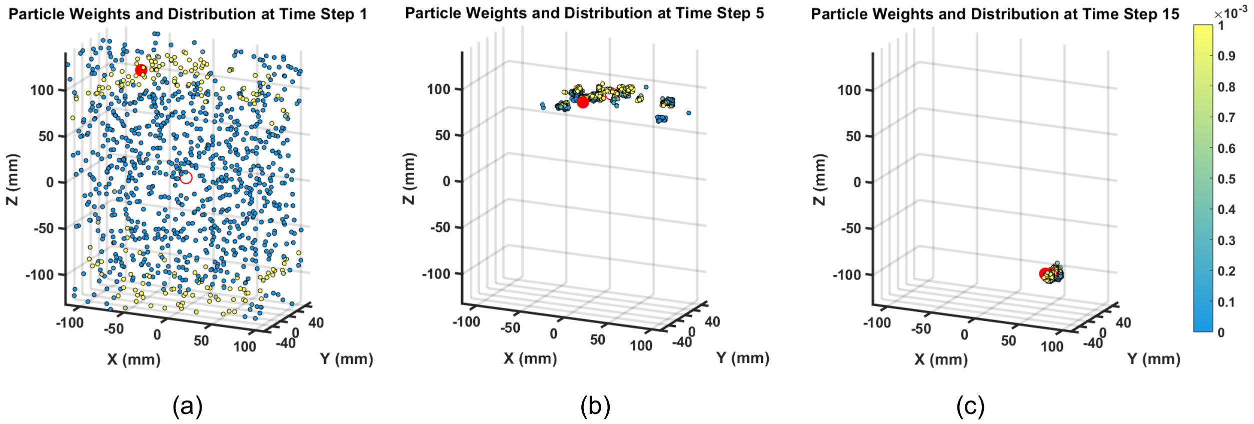

Fig. 2. The convergence processing of PF. The filled red dot represents the true position of the capsule, while the hollow red dot represents the estimated position. Small points represent each particle with color represents its weight. (a) Particle distributions at time step 1. (b) Particle distributions at time step 5. (c) Particle distributions at time step 15.

progressively updated based on displacement and mutual inductance (MI) between the Tx and Rx coils.

The architecture of the proposed system, as shown in Fig. 1, is divided into three parts. The first part is a belt-shaped Tx coil and its driving circuit, which generates a 6.78 MHz magnetic field. The second part is the capsule, comprising a Rx coil, an IMU and a microcontroller with a wireless transceiver. The third part is positioning algorithms on a remote workstation, such as a laptop. The capsule senses its motion and the MI, and transmits the data to the laptop. The positioning algorithms calculate the displacement between moving steps from the received data, then inputs these data to the PF to estimate the position of the capsule.

A. Particle Filter (PF)

The working process of the PF in this paper consists of three iterative steps: 1) particle propagation, 2) weight computation, and 3) resampling. In the first step, 1000 particles are uniformly distributed in the state space, which is the range of the digestive system in this work. Simultaneously, the initial observation of MI is passed on to the observation model to calculate the 'weight' of every particle. Secondly, particles are resampled based on their weights. Particles with lower weights are discarded, while those with higher weights are concentrated in regions closer to the estimated position. Subsequently, the approximate position of the capsule is calculated by the weighted average of the particles' states. Thirdly, the capsule keeps moving until it reaches the next time interval. The IMU provides the displacement during this period to the state transition model. The PF recalculates the weight and resamples again. The PF continues by repeating this process, allowing the approximate location to converge towards its true position with capsule movement.

The PF utilizes the current MI measurement z_t and the previous state $\mathbf{s}_{t\text{-}1} = [x, y, z]$ to recursively estimate the position of the capsule. During the calculation, two key equations are used: the state transition model (1) and the observation model (2).

$$\boldsymbol{s}_t \;=\; \boldsymbol{s}_{t\text{-}1} + \Delta\boldsymbol{d} + \boldsymbol{u}_t \tag{1}$$

$$z_t \;=\; f\left(V_{\mathrm{Rx},t}\right) + v_t \tag{2}$$

where t is the time index, $\boldsymbol{u}_t$ is the process noise. Here, process noise represents the displacement measurement error from the IMU. $\Delta\boldsymbol{d} = [\Delta x, \Delta y, \Delta z]$ is the displacement between the steps measured by the IMU. Equation (1) describes the state of the model, which is hidden or cannot be observed.

Equation (2) is used to describe the MI measurement process noise, where $V_{\mathrm{Rx},t}$ is the received voltage on Rx (see Section III) at time t, $f\left(V_{\mathrm{Rx},t}\right)$ is the measurement result of the MI at time t, and v_t is the observation noise that represents the MI measurement error. v_t is assumed to be independent $\boldsymbol{u}_t$, and both noise terms are modelled as Gaussian. With the two state equations above, the filtering distribution $p(\boldsymbol{s}_t|z_{1:t})$ can be expressed by (3) [9].

$$p(\boldsymbol{s}_t|z_{1:t}) \approx \sum_{i=1}^{N_s} w_t^i \delta\big(M\left(\boldsymbol{s}_t\right) - M\left(\boldsymbol{s}_t^i\right)\big). \tag{3}$$

Each particle is assigned a weight w_t^i, where i is the index of the particle and N_s is the total number of particles, δ is the Dirac delta impulse and all the weights sum up to one. The weights of particles are calculated by (4).

$$w_t^i \propto w_{t\text{-}1}^i p\big(z_t|M\left(\boldsymbol{s}_t^i\right)\big) \tag{4}$$

where the symbol ∝ signifies 'proportional to.', M is the mathematical model of the MI between two coils, which depends on their relative position based on Neuman's equation (5).

$$M \;=\; N_1 N_2 \frac{\mu_0}{4\pi} \oint\oint \frac{d\boldsymbol{l}_1 \cdot d\boldsymbol{l}_2}{r_{12}} \tag{5}$$

where $d\boldsymbol{l}_1$ and $d\boldsymbol{l}_2$ are infinitesimal elements of two coils, which are points on the Rx coil with $\boldsymbol{s}_t$ as the centre in polar coordinates. N_1 and N_2 are the number of turns of Tx and Rx coil, respectively, and r_{12} is the distance between these infinitesimal elements.

With (3) and (4), the estimated position $\hat{\boldsymbol{s}}_t$ can be calculated by the weighted average of the particles' states.

B. Inertial Measurement Unit and Inertial Navigation Systems Analysis

To measure the capsule movement in the body, its moving pattern needs to be analysed. There are two different movement types in the digestive system: peristalsis and segmentation [10]. Chyme, a semi-liquid mixture of food particles, moves in one direction rapidly during peristalsis, while moving slower and in both directions in segmentation movement. Peristalsis begins in the oesophagus, and segmentation movement exists in both the large intestine and

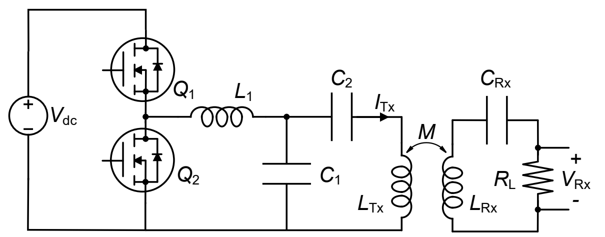

Fig. 3. Driving and receiver circuit configuration.

small intestine. This work focuses on the capsule movement in the intestines. Hence, segmentation movement is assumed as the moving pattern of the capsule. The feature of the segmentation is that it is moving back and forth, while there is a short time interval between movements. With these features, capsule movement is assumed to be stepwise, with a time interval between every movement. The movement of every step can be measured by the IMU. This movement $\Delta\boldsymbol{d}$ is used to update the state transition model in (1).

The method of using IMU to measure movement is commonly called inertial navigation systems (INS). INS calculates the position, velocity, and orientation of an object only by accelerometers and gyroscopes. This technology has been extensively applied in aerospace, automotive and various other industries. Since INS relies on Newton's second law of motion, the calculation process involves double integration, which causes errors to accumulate over time, leading to significant error accumulation and bias under long-term operational conditions [12].

In this paper, the initial velocity can be regularly reset to zero whenever the capsule changes movement direction. This movement pattern allows more accurate measurements of each step, as the reduced working time during these steps minimizes cumulative acceleration errors and biases.

III. Coil Design and Mutual Inductance Measurement

A. *Mutual Inductance Measurement with LCC Compensation Network*

Fig. 3 shows the circuit model of the inductive link. The system operates at a working frequency of 6.78 MHz within the industrial, scientific, and medical (ISM) band. As the capsule moves, the load on the Tx changes, resulting in variations in current. This change yields errors in MI calculation. To improve the accuracy of the positioning system, a LCC compensation network is implemented on the Tx. The current on the Tx coil I_{Tx} can be calculated using (6), when assumes Q_1 and Q_2 as ideal switches.

$$I_{\text{Tx}} = \frac{V_{\text{dc}}}{j\omega L_1} \tag{6}$$

where V_{dc} is the power supply voltage of the half-bridge inverter. L_1 is the inductance of the inductor in the compensation network. With the LCC compensation network, the current on the Tx coil remains constant. The MI at time t between coils can be measured by (7).

$$M = f\left(V_{\text{Rx},t}\right) = \frac{V_{\text{Rx},t}}{\omega I_{\text{Tx}}}. \tag{7}$$

B. *Coil Design*

To improve the wearability of the system, a circular belt-shape Tx coil is designed. A digestive system model is introduced for path reference [11]. The Tx coil is assumed to be located at the level of the middle part of the small intestine. The moving trajectory of the capsule is depicted along the small intestine, as shown in Fig. 4 (a). Based on this reference, the diameter of the Tx belt was set to 264 mm, and the range along the z-axis spans 250 mm from the highest to the lowest point. The radius of the Rx coil was set to 5 mm with 19 turns, and a height of 10 mm. The parameters of the coils and system are shown in Table I.

TABLE I. Coil and System Specifications

Parameter	Value
Operating frequency (f)	6.78 MHz
Tx coil radius (a)	132 mm
Tx coil turns (N_1)	2
Tx coil height	2 mm
Rx coil radius (b)	5 mm
Rx coil turns (N_2)	19
Rx coil height	10mm
Tx coil inductance (L_{Tx})	3.49 μH
Rx coil inductance (L_{Rx})	1.98 μH
Tx coil input voltage ($\lvert V_{in}\rvert$)	8 V
Load impedance (R_{L})	220 Ω

IV. Characterization of Particle Filter Behavior in Noisy Environments

A. *Simulation Setup*

The trajectory of the simulated capsule movement is shown in Fig. 4(b), which follows the small intestine trace from a digestive system model [11]. There are 83 points in total to simulate the movement of the capsule. These points served as the ground truth reference. The orientation of the Rx coil is fixed parallel to the Tx coil during motion. The centre of the Tx coil is set as the origin of the xy-plane, where z equals to 0, for the positioning calculation. The state space is $22.5 \times 11.5 \times 27\ \text{cm}^3$ to ensure that all particles are in the range of the digestive system. The range of the state space is set by edge points in the trajectory. It was set to be 20 mm wider than the trajectory range to allow particles to estimate positions near edges. The state space is also the FOV of the system. However, FOV can be proportional to change if the waistline and the size of the digestive system are changed.

B. *Simulation Results*

The performance of the PF was evaluated under different noise levels as a verification. The capsule movement was simulated with the trajectory in Fig. 4(b). The number of particles was set to 1000. During movements, the Rx coil remained parallel to the Tx coil. In real scenarios, the orientation of the Rx coil can be measured by the IMU.

There are two types of noise in PF: $\boldsymbol{u}_t$, the noise from displacement measurement, and v_t , the noise from MI measurement. Here, both types of noise were modelled as Gaussian [12], and added to the PF as described in (1) and (2). The root mean square error (RMSE) of the MI measurement was set to 0.03 nH, 0.1 nH, 0.5 nH, 1 nH, and 1.5 nH. The RMSE of the displacement measurement was set to 1 mm, 1.5 mm, 3 mm, 5 mm, and 8 mm to simulate the IMU with different noise performance. Fig. 5 compares the cumulative density function (CDF) of position error with different noise. The result of under 0.3 nH MI measurement with 3 mm displacement measurement RMSR is bolded in orange for better comparison. The position RMSE of this reference after

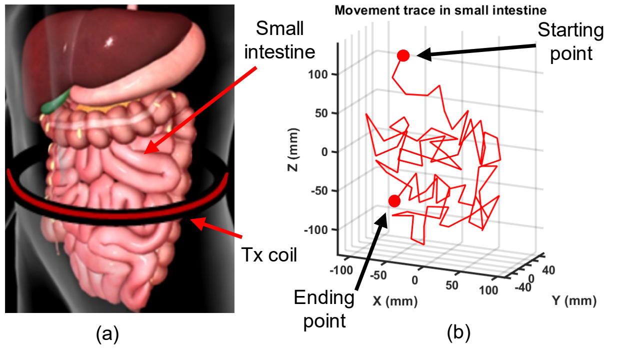

Fig. 4. Simulation setup. (a) Digestive system model [11]. (b) Trajectory of the capsule in the small intestine.

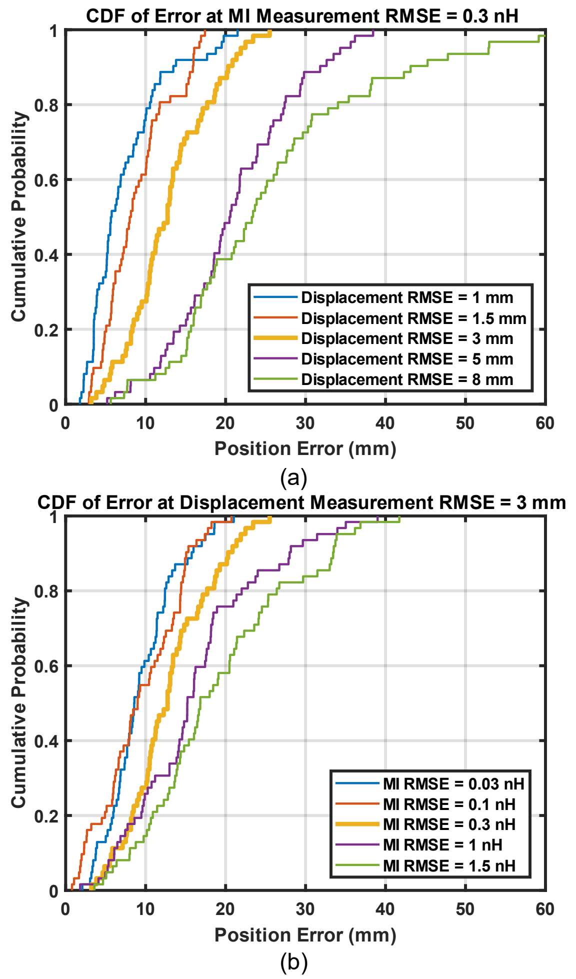

Fig. 5. Simulation results of PF after 20 steps with (a) 0.3 nH RMSE of MI measurement. (b) 3 mm RMSE of displacement measurement results.

20 steps is 13.89 mm with 80% of cases having errors less than 18mm, and all errors are below 25mm. From Fig. 5(b), the RMSE of the PF improves up to 10.32 mm with lower noise from MI measurement. By comparing Fig. 5(a) and Fig. 5(b), it can be seen that PF is more sensitive to noise from displacement measurements.

Table II compares this work to the state-of-the-art. This work offers the lightest Tx of only 73 g with 2.59 W Tx power consumption while ensuring the FOV of the system covers the digestive system. Moreover, the belt-shaped Tx coil offers flexibility to users with minimal constraints on their activities of daily life. The system can move easily with the user rather than being fixed in one position.

TABLE II. System Parameters Comparison

Reference	Nature Electronics'23 [2]		Electronics'23 [3]	TBCAS'24 [1]	This work
Positioning method	Magnetic field gradient		Magnetic Sensors	Mutual inductance	IMU and PF
Number of Tx coil	3		8-12	3	1
Turns of Tx coils	128, 128, 160		N.R.	10, 10, 10	2
FOV ($x \times y \times z$)	40 × 40 × 20 cm^3	N.R.	15 × 15 × 15 cm^3	N.R.	22.5 × 11.5 × 27 cm^3
Tx coil weight	18000 g	1200 g	N.R.	N.R.	73 g
Tx power required	800 W	60 W	N.R.	N.R.	2.59 W^a

N.R., not reported.
^{a}: Simulation.

V. Conclusion

A novel capsule positioning system has been presented. It uses a PF combined with IMU and a pair of coils. The system has a light belt-shaped Tx coil, which makes it easy to wear. A method using IMU to measure segmentation movement has been proposed by analysing the digestive system's movement pattern. The effect of noise on the PF has been analysed, with simulation results showing that the system is robust to noise from MI measurement errors. The system has 22.5 × 11.5 × 27 cm^3 FOV, a RMSE of 13.89 mm under noise and 2.59 W power consumption on Tx, according to simulation.

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