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Energy-Aware Error Correction Method for Indoor Positioning and Tracking

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***Abstract*—Indoor positioning is crucial for the effective use of drones in smart environments, enabling precise navigation and control in complex indoor spaces where GPS signals are weak or unavailable and wireless communication-based systems must be used. In order to improve positioning accuracy, various distance measurement techniques and related error correction methods have been proposed in the literature. However, these methods are mostly focused on accuracy and often require a significant amount of computational resources, which is quite inefficient when deployed on battery-operated devices like small robots or drones because of their limited battery capacity. Moreover, conventional error correction methods are little effective for the tracking of moving objects.**

In this paper, we first analyze the trade-off between energy consumption and accuracy for the error correction and identify the most energy-efficient error correction method. Based on this analysis in the accuracy/energy space, we introduce a new energy-efficient error correction method that is especially targeted for tracking a moving object. We validated our solution by implementing an Ultra-Wideband based indoor positioning system and demonstrated that the proposed method improves positioning accuracy by 15% and reduces energy consumption by 33% compared to the state-of-the-art method.

***Index Terms*—Indoor positioning system, energy-accuracy trade-off, error correction**

I. Introduction

Positioning systems are essential for tracking objects and enabling mobile devices to perform tasks autonomously. Global Positioning System (GPS), the most popular example of Global Navigation Satellite System (GNSS), is widely used for applications such as vehicle navigation and autonomous driving. However, when moving to indoor spaces, it is well-known that GNSS signals weaken or even fail due to physical barriers; therefore, indoor navigation and tracking must resort to wireless communication-based systems such as Wi-Fi, Bluetooth Low Energy, and Ultra-Wideband (UWB).

Typical indoor positioning systems (IPS) measure distances from a mobile target (called *tag*) to fixed devices placed in the same indoor space (call *anchors*), which play the equivalent role of satellites. Based on the measurement data between a tag and anchors (r_A, R_B, and r_C), the current position of the tag ($\hat{x}$, $\hat{y}$) is calculated through the measurement error correction and trilateration as shown in Fig. 1.

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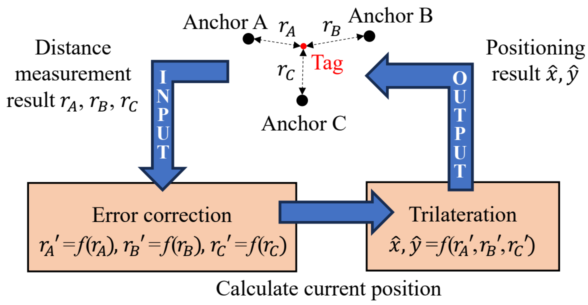

Fig. 1. IPS flow to obtain a position of a tag with three anchors.

State-of-the-art solutions are generally adaptations of GNSS-based methods and focus on reducing noise in measurement data to improve positioning accuracy. They often incorporate Kalman filter (KF) or machine learning techniques, which adjust the measured data based on experimental or historical data [1]–[4]. Although these methods generally achieve high accuracy, they often lead to high energy consumption due to the relatively long execution time. Spending a large amount of energy to enhance positioning accuracy is a critical issue for energy-constrained indoor mobility devices. This energy consumption directly reduces their operation time.

In this paper, we first propose a cost function to evaluate the energy consumed to improve positioning accuracy; based on this cost function, we analyze the trade-off between energy consumption and accuracy improvement for various error correction methods by classifying them in an accuracy/energy (cm/pJ) space. Based on this classification and analysis, we propose a novel correction method suitable for moving objects like drones. While most correction methods work based on historical data, the proposed method uses expected data to track the tag's moving position.

II. Energy-Aware Error Correction Method

We quantify the reduction in positioning error achieved through measurement correction methods and evaluate the associated energy consumption. The average positioning error PE is evaluated based on the gap between the estimated positions ($\hat{x}_n$ and $\hat{y}_n$) and the reference position (x and y) as

$$PE = \frac{1}{N}\sum_{n=1}^{N}\sqrt{(x-\hat{x}_n)^2+(y-\hat{y}_n)^2}. \tag{1}$$

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The standard deviation SD is defined as the gap between ($\hat{x}_n$ and $\hat{y}_n$) and the mean of the estimated position ($\bar{x}$ and $\bar{y}$):

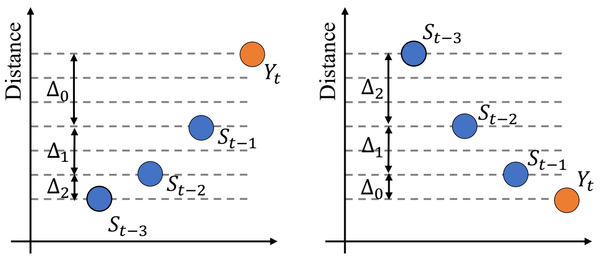
$$SD = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(\hat{x}_n - \bar{x})^2 + (\hat{y}_n - \bar{y})^2}. \quad (2)$$

While, E represents the overall energy consumption for the IPS flow including a given correction method.

One of the simple but effective error correction methods from the perspective of energy efficiency is exponential smoothing (ES). This method generates current-estimated data S_t by considering both history-based data Y_t and the measured data X_t at time t. The equation of the S_t by ES is the following

$$S_t = \alpha X_t + (1-\alpha)Y_t$$

where α is the smoothing factor. Y_t has various functions depending on the type of the smoothing methods. In the case of single ES (SES), Y_t equals to S_{t-1}, which represents the previous estimated data.



(a) Increase in distance. (b) Decrease in distance.

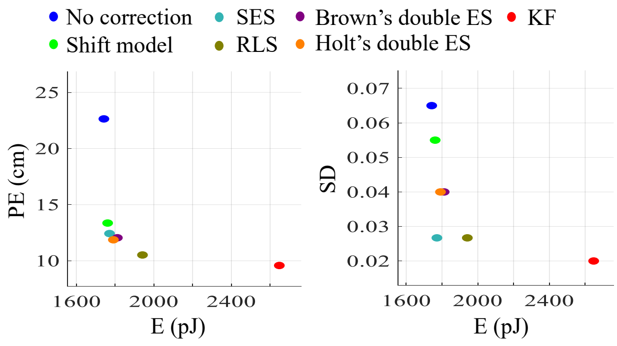
Fig. 2. Estimation of Y_t based on the previous S_{t-T}.

The ES is well-suited for correcting data that changes gradually due to its nature of utilizing past data. However, it tends to produce substantial errors when abrupt changes occur, even if an overall trend is present. We propose a method to predict the history-based data when the measured data change sharply. Fig. 2 shows the calculation of Y_t based on the change of previous estimated data S_{t-3}, S_{t-2}, and S_{t-1} when the measured distance changes sharply. By calculating the rate of change between these data, it adjusts the predictions to maintain smooth tracking during abrupt variations. This proposed method not only performs smoothing but also incorporates a rapid change in distance. So, it is possible to improve positioning accuracy under the limited amount of calculations.

III. Experimental Results

We implement the UWB based IPS to measure distances to anchors and analyze PE and SD by E as shown in Fig. 3. A blue dot in each graph means no correction result that is located at the lowest energy consumption but highest error in both of PE and SD. The KF achieves the lowest PE and SD, but requires the highest energy consumption. Other methods fall somewhere in between. Among them, SES looks very efficient in this trade-off in terms of PE and SD.

We pick KF as the most accurate method, SES as the simplest method, and the proposed method to compare PE and SD for moving object SD_m. The energy consumption of the proposed



(a) (b)

Fig. 3. (a) E-PE trade-off and (b) E-SD trade-off.

method is nearly the same as SES. Fig. 4 shows that the proposed method achieves 12.7% lower PE with 33% less energy than KF. Also, compared to SES, PE is reduced up to 15% with nearly the same energy consumption that means 96% and 23% reduction of C_{PE} and C_{SD_m}, respectively. It is confirmed that the proposed method effectively achieves accuracy without increasing the clock frequency or performing complex operations.

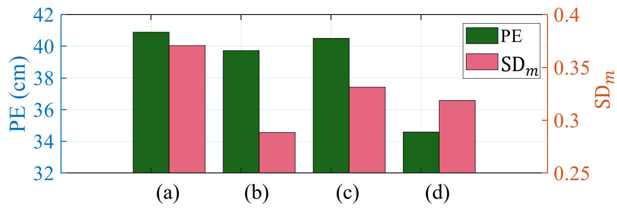


Fig. 4. Comparison of correction methods for moving object: (a) no correction, (b) KF, (c) SES, and (d) Proposed method.

IV. Conclusion

Energy-aware indoor positioning and tracking are becoming more and more important as the production system expands through smart factories. However, typical approaches are only suitable for large systems with huge energy storage. In this paper, we analyze the energy and positioning error trade-off and suggest the energy-efficient error correction method for moving object. The proposed IPS can be actively utilized for optimal indoor driving of ultra-small robots or unmanned aerial vehicles that must operate only with fairly limited batteries.

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