An Improved Indoor Localization Solution Using a Hybrid UWB-Doppler System with Kalman Filter

Jing Wang[1], Yao Tang[1], José-María Muñoz-Ferreras[2], Roberto Gómez-García[2], and Changzhi Li[1]

[1]Department of Electrical and Computer Engineering, Texas Tech University, Lubbock, USA
[2]Department of Signal Theory & Communications, University of Alcalá, Alcalá de Henares, Spain

***Abstract* — Ultra-wideband (UWB) positioning system has gained much attention in the field of indoor localization due to its various advantages. The narrow pulse nature of UWB signal results in a very large bandwidth which enables high resolution positioning, low loss penetration, and low cost. However, practically, the low transmit power severely restrains the transmission range of UWB signal so that it is only suitable for short-range accurate ranging. Therefore, a novel hybrid UWB-Doppler system was proposed by using a fixed UWB positioning system monitored region to calibrate the accumulated error of a Doppler-gyroscope trajectory-tracking system. In this paper, we present improved indoor localization performance using the hybrid UWB-Doppler system employing the Kalman Filter. Experiments were conducted in a large complex indoor environment to further demonstrate the feasibility of the proposed indoor localization method.**

***Index Terms* — Ultra-wideband (UWB), Doppler, radar, Kalman Filter, indoor, localization.**

I. Introduction

Indoor localization is creating a large potential market because of its wide range of applications in human daily life such as package tracking, surgery assistance, and indoor guidance. Various indoor localization techniques have been proposed, which can be divided into two categories: building dependent and building independent [1]. Building dependent technologies such as Ultra-wideband (UWB), RFID and WiFi fingerprint mainly rely on the pre-installed infrastructure in the building. However, this may call for high installation and maintenance cost. On the other hand, building independent technologies do not require any infrastructure support, but each method in this category has its own shortcomings and limitations. Therefore, multiple technologies can be used concurrently to combine the strengths of each one while overcoming their weaknesses.

UWB positioning has become a promising solution for indoor target localization, tracking, and accuracy-critical applications because of its high range resolution, high penetration capability, and low cost. However, due to the constraints on transmit power, the received UWB signals can be too weak to be detected after penetrating through obstacles or long-distance transmission. As a result, the UWB positioning system is only suitable for short-range localization unless more UWB base stations are installed, which in turn increases the overall cost. Among all the building independent technologies, radar-based localization systems offer the benefits of high accuracy, increased security, and robustness against ambient light change. Especially, Doppler radar can accurately detect displacement with simple structure, efficient algorithm, and easy deployment [2]. Inertial measurement units (IMU) are attractive for being compact, lightweight, and inexpensive. However, the accumulated errors over time should be addressed for reliable performance.

In previous work [3], a hybrid UWB-Doppler system was designed for short-range indoor localization, where a UWB positioning subsystem monitors a small region as a check point to remove the error accumulated in the Doppler-gyroscope measurement. However, a considerable amount of overall error exists in the performed experiments, which is mainly induced by the random drift of the UWB data in the angle calibration process. Thus, trajectory optimization is inevitable for mitigating the UWB drift, enhancing measurement accuracy, and improving system robustness.

To further improve the performance, this paper uses Kalman Filter as one of the trajectory optimization techniques because of the light computation load and real-time processing capability. The tracking theory that leverages Kalman filter will be explained. Long-term experiments conducted in a complex office area will be presented and the results will be analyzed.

II. Kalman Filter Assisted Tracking Theory

A. Hybrid UWB-Doppler System

In the hybrid UWB-Doppler system, an equilateral UWB-accurate area is set up with three UWB base stations placed at known locations so that the central region of this area has the minimum positioning error [4]. The distance between the paired UWB tag and the three base stations is obtained through double-sided two-way ranging (DS-TWR) algorithm. Trilateration algorithm is applied to estimate the absolute location (x_i, y_i) at time i of the subject who has the tag attached. The heading direction θ of the next location (x_{i+1}, y_{i+1}) can then be calculated using $\theta = \tan^{-1}((y_{i+1} - y_i)/(\mathrm{x}_{i+1} - \mathrm{x}_i))$. Outside of this UWB-accurate area,

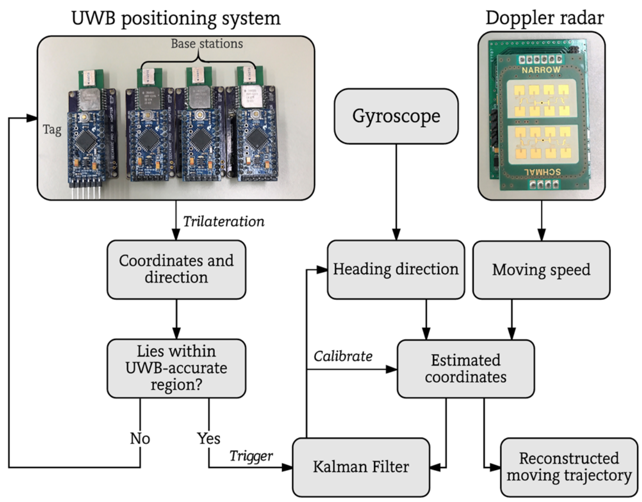

Fig. 1. Operation flow chart of the hybrid UWB-Doppler system aided with Kalman Filter.

trajectory tracking is realized by a K-band Doppler radar with the aid of a three-axis digital gyroscope. The speed vector of the moving subject which carries the Doppler-gyroscope trajectory-tracking system can be obtained from the measured Doppler frequency. The digital gyroscope constantly senses the moving direction. By integrating the measured velocity in each direction over time, movement trajectory can be reconstructed. However, because of this integration process, measurement errors are accumulated along with time of operation and can cause significant performance degradation. Therefore, the predefined UWB-accurate region serves as a calibration area in a way that every time a subject walks into this area, the accumulated errors are removed by applying Kalman Filter process until the subject moves out of this area. The operation of the hybrid UWB-Doppler system aided with Kalman Filter is demonstrated in Fig. 1. Details of the Kalman Filtering are explained below.

B. Kalman Filter Algorithm

Since only the coordinate of the subject is of major concern during the Kalman Filter process, a conventional one-dimensional Kalman Filter algorithm is selected to smooth out the random drift of the UWB results in the location calibration stage. The operation of Kalman Filter algorithm contains two steps: status prediction and status update.

The status prediction step is presented in the following two equations:

$$\begin{cases} X_t = X_{t-1} \\ P_t = P_{t-1} + Q \end{cases} \quad (1)$$

where X stands for coordinate estimate, P stands for error estimate, Q is the process noise, and t represents the discrete time step with $t \geq 0$. The measurement update with K

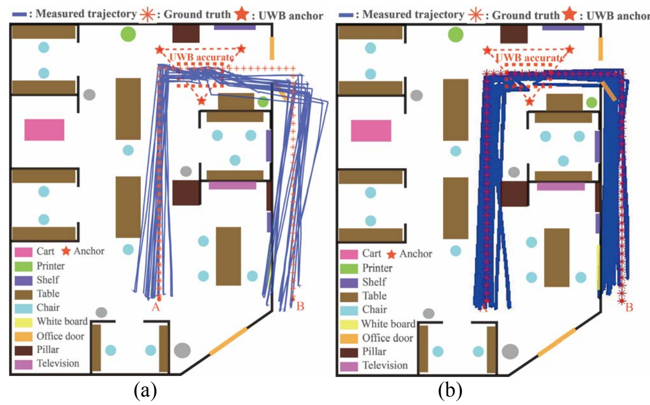

Fig. 2 (a) Measured short-range trajectory by the hybrid UWB-Doppler system. (b) Measured short-range trajectory by the hybrid UWB-Doppler system with Kalman Filter.

denoting Kalman gain, R representing measurement noise, and Z as measured data can be calculated as:

$$\begin{cases} K_t = P_t / (P_t + R) \\ X_t = X_{t-1} + K_t \bullet (Z_t - X_{t-1}) \\ P_t = (1 - K_t) \bullet P_{t-1} \end{cases} \quad (2)$$

When a subject steps into the UWB-monitored calibration region, the Kalman filtering process will be triggered and the coordinate measured by the Doppler-gyroscope system at this time t will be treated as the initial value while the UWB-obtained results will serve as the measurement data. Hence, Kalman Filter helps optimize the UWB measurements by alleviating the random drift. In the meantime, the movement direction is updated using the output data from the Kalman Filter. For this reason, not only is the UWB random variation mitigated, but also a better heading direction estimation is obtained. It should be noted that tweaking the values of Q and R are essential for optimal performance.

III. Experiment

The advantage of the hybrid UWB-Doppler system has been tested in previous experiments [3]. Experiments were conducted in a typical office environment. System setup consisted of an UWB positioning subsystem, a K-band Doppler radar, and a three-axis digital gyroscope. The UWB positioning subsystem uses DecaWave DWM1000 transceiver with center frequency of 6.5 GHz. A commercial InnoSent IPS-154 Doppler radar working at 24.125 GHz is equipped with a 2×4 patch antenna array. A walking path was taped on the floor which served as the trajectory ground truth. The UWB check point was formed around the mid-way of the walking path using three base stations. The hybrid system was attached on a human subject to be tracked. A human subject completed ten movement cycles in 20 minutes with

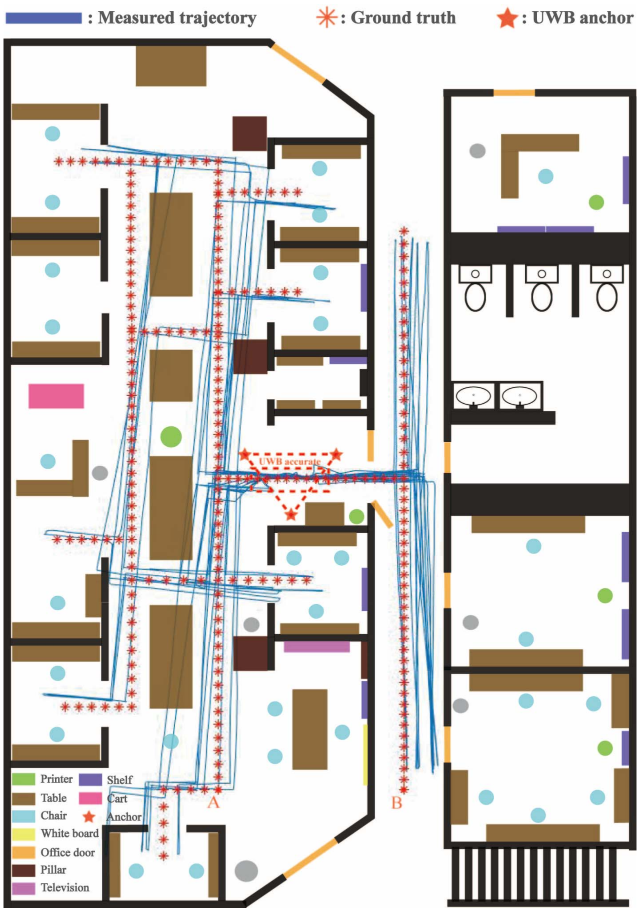

Fig. 3. Measured random movements by the hybrid UWB-Doppler system with Kalman Filter.

starting point A and ending point B. Doppler radar data was received by the laptop through the microphone port and digitized by the ADC embedded in the sound card. An Arduino microcontroller board and a Bluetooth module were used to wirelessly transmit gyroscope data to the laptop. The UWB subsystem measured coordinates were send to the laptop through USB port. The measured trajectory in Fig. 2 (a) is the same as in [3] which is before the use of Kalman Filter. After applying the Kalman Filter, the overall error was well-controlled in a more confined range, as can be been in Fig. 2 (b).

To further demonstrate the feasibility of the proposed improved localization method, a longer, more complex experiment was conducted in an expanded area. The same system setup was used as the previous experiment [3], with the difference being the moving pattern. To better simulate a real-world scenario in the indoor office area, the subject walked randomly along different paths for a total of 30 minutes. Fig. 3 clearly shows that the moving trajectory obtained using the improved indoor localization method is robust enough to provide reliable indoor tracking performance.

However, it has been observed in Fig. 3 that the areas furthest away from the calibration region have the worst accuracy. This is because large accumulated position errors arise when they are not removed in a timely manner. A possible solution could be setting up a few more UWB calibration regions to increase the chances of the subject walking into them at the cost of increased installation and maintenance fees. By properly choosing the location of the calibration areas, complete trajectory tracking of the floor should be achievable.

IV. Conclusion

An improved indoor localization approach using a hybrid UWB-Doppler system with Kalman Filter was presented. The optimized measured trajectory with the use of Kalman Filter has shown better performance with more confined error range. The potential of such method for practical indoor localization was demonstrated in a complex indoor environment. Future work will focus on increasing the number of UWB calibration regions for larger area implementation and the balance of error control and system cost.

Acknowledgment

The authors gratefully acknowledge grant support from National Science Foundation (NSF) ECCS-1254838.

References

[1] A. Alarifi, A. Al-Salman, M. Alsaleh, A. Alnafessah, S. Al-Hadhrami, M. Al-Ammar, H. Al-Khalifaet, "Ultra wideband indoor positioning technologies: Analysis and recent advances," *Sensors*, vol. 16, no. 5, 707, May 2016.

[2] Y. Tang, C. Li, "Wearable indoor position tracking using onboard K-band Doppler radar and digital gyroscope," *2015 IEEE MTT-S 2015 International Microwave Workshop Series on RF and Wireless Technologies for Biomedical and Healthcare Applications (IMWS-BIO)*, Taipei, Sept. 2015, pp. 76-77.

[3] Y. Tang, J. Wang, C. Li, "Short-range indoor localization using a hybrid Doppler-UWB System," *2017 IEEE MTT-S International Microwave Symposium (IMS)*, Honolulu, HI. Jun. 2017, pp. 1-3.

[4] Y. Chen, J. Francisco, W. Trappe, R. P. Martin, "A practical approach to landmark deployment for indoor localization," *2006 3rd Annual IEEE Communications Society on Sensor and Ad Hoc Communications and Networks*, Reston, VA, USA, Sept. 2006, pp. 365-373.