Directional Ranging for Enhanced Performance of Aided Pedestrian Inertial Navigation

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***Abstract*—We present a ranging-based aiding method for pedestrian inertial navigation, utilizing not only ranging readouts, but also orientation of the ranging sensors. Both numerical and experimental results demonstrated improvements in navigation accuracy using the method. Kalman Filter (KF) was implemented to merge inertial navigation with Zero-Velocity-Update (ZUPT) algorithm and foot-to-foot directional ranging information. The improvement of navigation accuracy was achieved purely algorithmically without any increase in complexity of the hardware. We demonstrated experimentally that the navigation errors can be improved by about two times using the method.**

Index Terms*—*pedestrian inertial navigation; directional ranging; ZUPT; Kalman filter

I. Introduction

Self-contained pedestrian inertial navigation is made possible with the development of Micro-Electro-Mechanical Systems (MEMS)-based Inertial Measurement Units (IMUs). However, due to a relatively high noise level and scale factor instability of MEMS-based IMUs, there is a need for compensation mechanism to suppress error accumulation and thus extend the range of precision navigation. ZUPT algorithm [1] and foot-to-foot ranging [2] are two techniques that are commonly used for self-contained navigation.

ZUPT algorithm has been demonstrated to reduce the navigation error growth, but it cannot compensate for errors in yaw angle, making it the main error source in the ZUPT-aided navigation [3]. ZUPT algorithms can be enhanced by relative measurements, for example by measuring the distance between two feet using ultrasonic range sensors. In this straightforward implementation, the measurement helps as an aiding information, but is not directly correlated with the yaw angle. This paper intends to fill the gap by introducing the directional ranging, a technique providing not only the distance, but also a relative orientation between the feet, utilizing the same hardware as the regular foot-to-foot ranging.

II. Directional Ranging

The purpose of directional ranging is to take advantage of directionality of the ranging sensor to improve the navigation accuracy. In our experimental setup, Fig. 1(a), we separated the transmitter and the receiver of the ranging system to two feet instead of placing them on the same foot. The output of the ranging system is zero if the transmitter and the receiver are not aligned. The major advantage of setup in Fig. 1(a) is the ability to measure the distance between the transmitter and the receiver and a relative orientation between the two feet. When the transmitter and the receiver are aligned, Fig. 1(b), the ranging system obtains the distance information. The full alignment requires two conditions: (1) feet are aligned along the direction of transmission of the ultrasonic wave, and a counter-example is in Fig. 1(c), and (2) yaw angles are the same for both feet, and a counter-example is in Fig. 1(d). The two conditions can be mathematically expressed as

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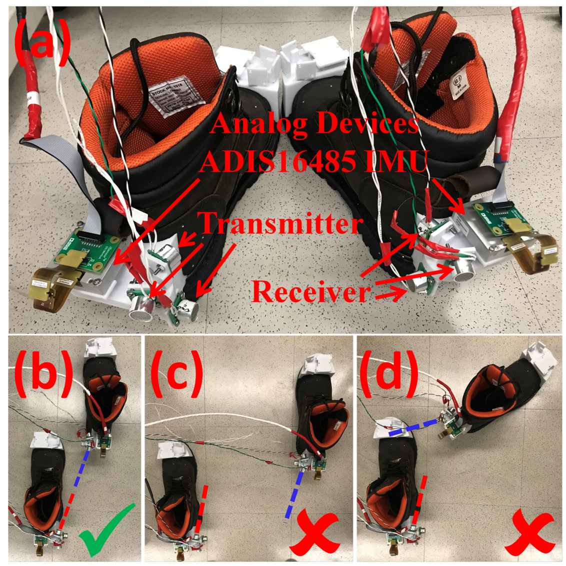

Fig. 1. (a) Experimental setup of this study; (b) Ranging data are collected with transmitter and receiver aligned; (c)-(d) Ranging data are not collected with transmitter and receiver misaligned. Dashed lines in (b)-(d) are directions of transmission of the ultrasonic wave.

$$\arctan\frac{N_l - N_r}{E_l - E_r} - Yaw_r = \pm 75^\circ, \tag{1}$$

$$Yaw_r - Yaw_l = 0, \tag{2}$$

where Yaw, N, and E correspond to the yaw angle, and positions along the North and the East, respectively. The subscripts l and r indicate the left foot and the right foot.

III. Experimental Setup

For this study, we developed a customized testbed for sensor fusion of multiple IMUs and ranging sensors for self-contained navigation experiments [4]. Collected data were acquired by a National Instruments-CompactRIO (cRIO-9039) with programmable FPGA Xilinx Kintex-7 and a real-time processor

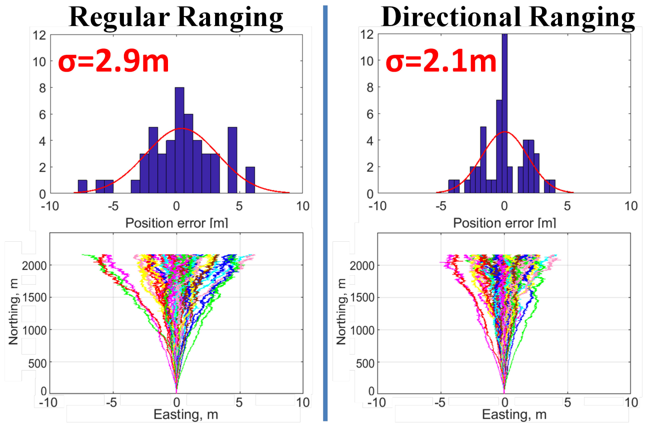

Fig. 2. Comparison of navigation results with regular ranging (left) and directional ranging (right). In the bottom row are 50 trajectories with simulated IMU and ranging data. In the top row are the corresponding distributions of the final estimated position errors.

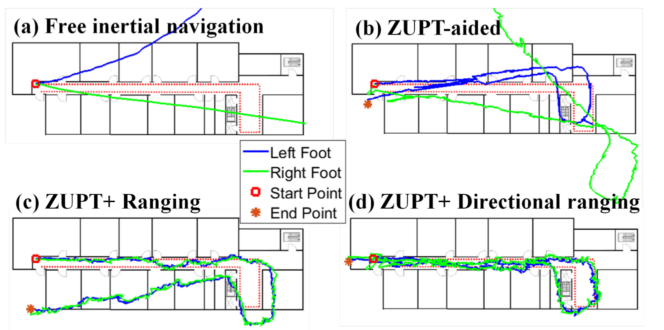

Fig. 3. A comparison of results of different aiding techniques for indoor environment. The red dashed line is the real trajectory.

1.91 GHz Intel quad-core. Two tactical-grade six degrees of freedom MEMS IMUs (Analog Devices ADIS16485) and two ultrasonic range finders (Devantech SRF08) were aligned and fixed to left and right boots by 3D-printed fixtures. One IMU was attached to each foot to track the motion. Two ranging systems were placed to obtain information for two different phases during walking – left foot in front and right foot in front. The fused data were transferred to the workstation for processing at 100Hz with 16-bit resolution.

IV. Results

Numerical simulations were conducted to verify the effects of directional ranging. IMU data and ranging sensor data were first extracted from human gait model developed in [5]. The trajectory was a straight line toward the North and the total navigation time was 25 minutes. IMUs were assumed to be tactical grade with Angle Random Walk of 0.2deg/rt(hr) and Velocity Random Walk of 0.1mg/rt(Hz). Ranging sensor accuracy was assumed to be 1cm. The results are presented in Fig. 2. On the left, 50 trajectories with random noise characteristics are estimated with inertial navigation algorithm augmented by ZUPT + ranging algorithm; on the right, 50 trajectories are estimated with directional ranging instead of regular ranging. The standard deviation of the position error was estimated to reduce from 2.9m to 2.1m.

Experiments were conducted both indoors and outdoors, and in both cases only self-contained navigation was used (no aiding, such as GPS, WiFi, LTE, etc.). The indoor test had a total navigation time of about 3 minutes. The results with different navigation algorithms are shown in Fig. 3. It was demonstrated that ZUPT algorithm suppressed the navigation error, but the yaw angle error was not compensated, Fig. 3(b). Ranging algorithm partially compensated for the yaw angle error, Fig. 3(c), while the directional ranging algorithm further improved it and therefore reduced the overall navigation errors by 1.8 times as compared with the regular ranging, Fig. 3(d). The experimental navigation error was greater than in simulation. A possible reason is that a real motion of the foot is 3D, while in simulation, changes of roll and yaw angles were neglected.

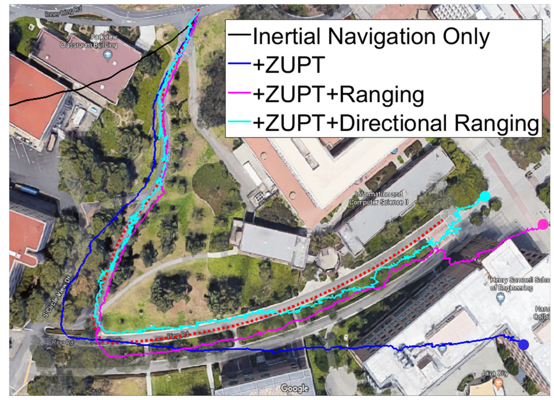

Fig. 4. A comparison of different aiding techniques for self-contained navigation. The red dashed line is the real trajectory.

Outdoor navigation experiment was conducted with the navigation time of about 6 minutes and the total navigation length of around 420m. The estimated trajectories by different ranging techniques are presented in Fig. 4. Estimation error of position was reduced from 25m to 10m by implementing directional ranging instead of regular ranging.

V. Conclusions

The directional ranging was proposed and verified both numerically and experimentally. The navigation error was reduced by about 2 times, as demonstrated experimentally, showing an advantage of the directional ranging approach. We conclude that the directional ranging has benefits and yields lower navigation errors than regular ranging. We anticipate that further improvement could be made by implementing ranging sensors with narrower ultrasonic beams to improve the accuracy of orientation measurements.

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