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UWB Sensor Placement for Foot-to-foot Ranging in Dual-foot Mounted ZUPT-aided INS

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Abstract—This paper studies the impact of the ultra-wideband (UWB) sensor placement for a Zero velocity update (ZUPT)-aided pedestrian inertial navigation solution that uses a foot-to-foot ranging feedback to improve its localization accuracy. Several sensor configurations are investigated in both static and dynamic cases. The Root Mean Square Error (RMSE) is used as the performance metric for the static measurement accuracy while the Circular Error Probable (CEP) is chosen to evaluate the sensor configurations in dynamic experiments.

Index Terms—Ultra-wideband (UWB), sensor placement, foot-to-foot ranging, pedestrian inertial navigation, zero velocity update (ZUPT)

I. INTRODUCTION

Pedestrian localization and tracking are of interest in applications such as locating firefighters or rescuers in buildings, tracking miners working underground, and navigating soldiers on the battlefield [1]. For the indoor pedestrian localization, where the Global Navigation Satellite System (GNSS) is usually challenged, the pedestrian dead-reckoning (PDR) or pedestrian inertial navigation system (INS) works as an infrastructure-free self-contained navigation system that does not rely on external signals or pre-installed beacons and landmarks [2]. But, the localization solution merely based on the INS suffers from high drifts in the position estimation due to a relatively high noise level and unknown time-varying biases in the inertial measurement unit (IMU) measurements. To reduce the growth rate of errors in foot-mounted INS, the zero velocity update (ZUPT) approach is frequently used [3]. ZUPT uses human-legged locomotion and detects the phases of the gate to re-calibrate inertial sensors during the rest phases of the foot. Nonetheless, the ZUPT's performance depends on the pre-determined ZUPT threshold, and it has a systematic error, which becomes significant for long-term navigation. To bound the INS localization error further, in the case of dual foot-mount INS systems, foot-to-foot relative range measurement feedback has been proposed to aid the INS system [4], [5].

Sensory systems such as sonars [6], ultrasonic sensors [7], and vision-based techniques have been used to measure the foot-to-foot relative range [5]. However, these sensory systems suffer from measurement discontinuity switching from line-of-sight (LoS) to non-line-of-sight (NLoS) scenarios where the measurements are unavailable due to obstructions between feet. In ultrasonic sensors, because of the feet's relative motion, it is also possible that the omitted signal reflects away instead of back, resulting in no or incorrect distance measurements [5]. On the other hand, vision-based sensors cause an increase in hardware complexity and computational cost, which are not preferable for embedded systems.

In this letter, we propose to use foot-mounted ultra-wideband (UWB) sensors to measure the foot-to-foot range. Our choice is motivated by a relatively high time resolution, wide bandwidth, and a capability to work under NLoS scenarios of the UWB sensors. UWB uses a time-of-flight (ToF) approach for ranging. UWB signals have good penetration ability, providing measurements in NLoS conditions, as well. UWB ranging has already been used in cooperative navigation scenarios where inter-pedestrian ranging feedback is used to improve the localization accuracy of the foot-mounted INS of communicating pedestrians [8], [9]. In such scenarios, however, the UWB sensors are mounted on the shoulder. UWB is a radio frequency (RF) signal whose performance can be affected by the transceivers' height from the ground. The relative orientation of the UWB transceivers can also affect the ranging performance. Therefore, to obtain high accuracy UWB range measurements with a low bias for foot-to-foot ranging, in this letter, we investigate the dual-foot mounted UWB sensor placement. To the best of the authors' knowledge, no systematic study has been conducted on how the UWB sensor placement on foot affects the ZUPT-aided pedestrian inertial navigation. Our investigation method includes first exploring the effect of the UWB placement, height, and relative orientation on the foot-to-foot ranging performance when the feet are stationary. Next, we investigate how different placements affect the performance of the ZUPT-aided pedestrian inertial navigation. The Root Mean Square Error (RMSE) is used as the performance metric for the static measurement accuracy. The Circular Error Probable (CEP) is chosen to evaluate the sensor configurations in dynamic experiments. In our experimental study, we used the DWM1000 UWB transceiver, one of the most popular UWB transceivers on the market.

II. UWB SENSOR PLACEMENT

This section reports on the effect of the UWB sensor placement on the foot-to-foot ranging, and subsequently, on the localization accuracy of a dual-foot mounted ZUPT-aided INS. The testbed we used to collect the data, called the Lab-On-Shoe platform, is shown in Fig. 1. Detailed description of the Lab-On-Shoe platform can be found in [10] and [11]. The raw measurements obtained from the UWB sensors are the range and the signal power metric (PM). The PM is a popular measure that is used for NLoS UWB signal identification [12], [13]. PM is the difference between the total received signal power and the direct-path signal power. The principle behind the power-based NLoS identification method is that in LoS condition, the power of the received direct-path signal takes a big proportion of the total received signal power, while in NLoS condition the direct-path is significantly attenuated or even completely blocked. When the difference between

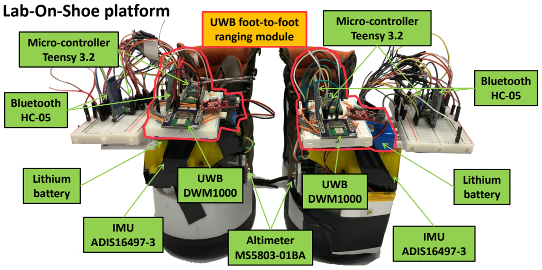


Fig. 1 – The Lab-On-Shoe platform.

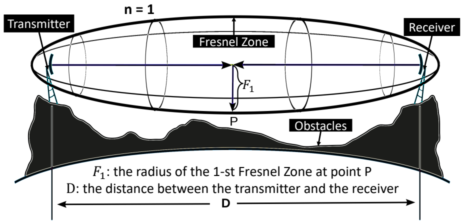


Fig. 2 – The first Fresnel zone.

total received power and the direct-path power, which is the PM, is larger than a threshold value, the range measurement is identified as NLoS [12]. The performance of this approach, however, depends highly on the choice of the discrimination threshold value. When UWB sensors are installed well above the ground (for example on shoulders), the threshold used for a PM-based NLoS discriminator is 6 dBm, that is any signal with PM value above 6 dBm is identified as NLoS [12], [13].

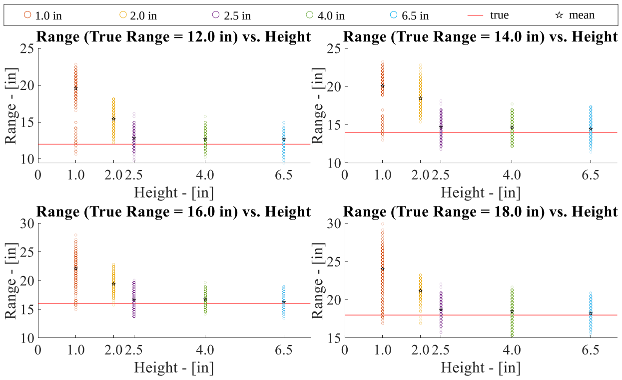
A. Ground Effect

Due to the Fresnel zone effect [14], as shown in Fig. 2, the height above the ground at which the UWB sensors are placed affects the range measurement. A Fresnel zone is one of a series of confocal prolate ellipsoidal regions of space around a transmitter and a receiver. The obstacles inside the Fresnel zone can cause a significant interference in signal propagation between receiver and transmitter. Fresnel zone computations are used to anticipate obstacle clearances. On the other hand, the location of the transmitter and the receiver can be designed to avoid obstacles based on the Fresnel zone. Intuitively, clear LoS between the transmitter and the receiver guarantees the accuracy of UWB range measurements. But, because of the complex nature of the radio waves, obstructions within the first Fresnel zone can cause a significant weakness even if those obstructions are not blocking the apparent LoS signal path. For example, suppose the two UWB sensors are placed in LoS condition but not high enough above the ground and not close enough to each other. Then, the ground can be an obstacle inside of the first Fresnel zone, causing a significant impact on the signal strength. This phenomenon is known as the ground effect on UWB measurements.

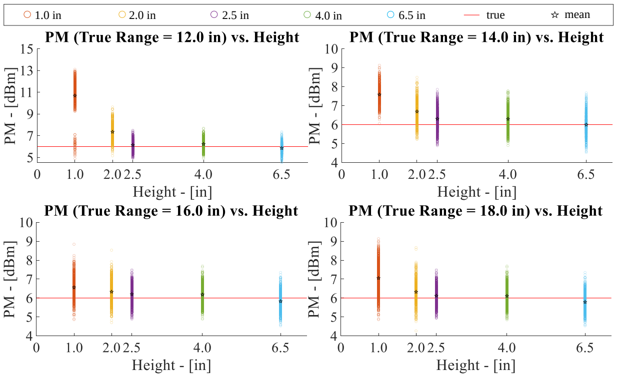
Based on the distance between two parallel feet and the frequency of the UWB signal of the Decaware DWM1000 module, we calculated the radius of the first Fresnel zone F_1 according to (1)

$$F_1 = 0.5\sqrt{c\,\mathsf{D}/f}, \tag{1}$$

where c is the speed of light, D is the distance between the transmitter and the receiver mounted on the feet, and f is the frequency of the transmitted signal. Given that the foot-to-foot distance is 12 in



(a) Range vs. Height



(b) PM vs. Height

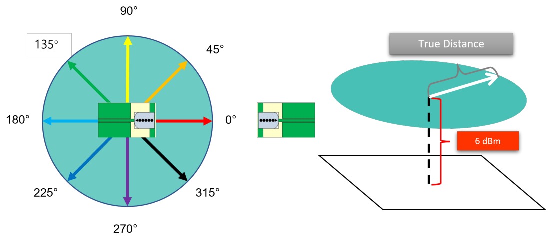
Fig. 3 – The range and PM values at different heights and distances. In each height/distance pair, 1000 measurement samples are taken.

(standing parallel), and the frequency of the UWB signal of DWM 1000 sensors is 6.5 GHz, based on (1), the theoretical radius of the first Fresnel zone is 0.06 m. Therefore, the two UWB sensors should be placed at least 0.06 m above the ground to avoid the ground effect.

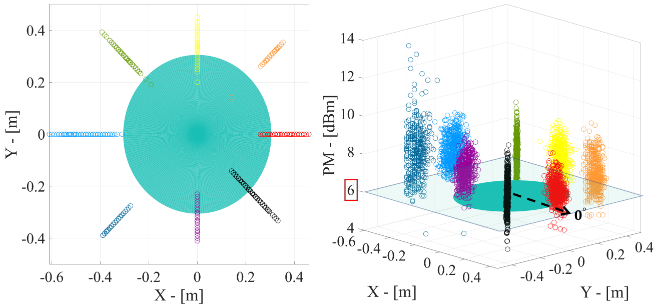
The minimum height obtained by the Fresnel zone criterion is a theoretical value. We tested the effect of the height on the ranging accuracy and the PM value of the DWM1000 UWB sensors by placing two UWB transceivers face-to-face (at 0° angle shown in Fig. 4(a)) and at different heights of 1.0, 2.0, 2.5, 4.0, and 6.5 inches and ranges of 12, 14, 16 and 18 inches from each other. The results are shown in Fig. 3. Fig. 3(a) clearly shows the adverse effect of approaching close to the ground on ranging accuracy, as predicted by the Fresnel zone study. Notice that the recommended height of 0.06 m ≈ 2.36 in by the Fresnel zone analysis when UWB sensors are 12 in apart correlates well with the experimental value observed in Fig. 3(a). With regards to PM value, we can see in Fig. 3(b) that the deterministic threshold of 6 dBm is not respected well when sensors are closer to ground. Only at the height of 6.5 in the average PM value starts to go under 6 dBm. Recall that PM values below 6 dBm indicated LoS measurements. This phenomenon can be resulted from the multipath propagation due to ground effects.

B. Orientation Effect

Besides the UWB sensors' height from the ground, the relative orientation of the transceivers also affects the accuracy of UWB ranging. To find an optimal relative orientation for the UWB sensors placed on the Lab-on-Shoe, we collected raw measurements at 8



(a) Schematic



(b) Measurement Cloud

Fig. 4 – UWB sensor measurements at various relative angles when they are 12 in apart and 6 in above the ground. (a) is the schematic for the collected data cloud in (b).

relative angles shown in Fig. 4 (a). The UWB sensors were placed at 6.0 in (0.1524 m) above the ground, which is the same height that the UWB sensors are from ground on Lab-on-Shoe platform and 12.0 in (0.3048 m) from each other. The collected data is visualized in Fig. 4 (b). The radius of the solid green circle is the actual distance between the sensors (12.0 in). The sensors' location is shown in the $X-Y$ plane, with one of them placed fixed at the center and the other one placed at different relative angles as shown in Fig. 4 (a). The optimal relative orientation to place the UWB sensors is when the empirical mean of the collected measurements is on the perimeter of the green circle (to have zero mean Gaussian distribution). According to the results showing RMSE of the UWB range measurements at different orientations, Fig. 4 (b) and Table 1, we concluded that the optimal configuration to place the UWB sensors on the Lab-on-Shoe platform is when the sensors are at 270° relative orientation.

On the right-hand side plot in Fig. 4 (b), the Z axis denotes the PM, and the green circle is in the 6 dBm plane, which represents the deterministic threshold used in literature [12] to discriminate LoS and NLoS when the sensors are placed well above the ground. This experimental study, given that all the measurements are collected in clear LoS, similar to the results in Fig. 3(b), indicates that the PM value of 6 dBm is not the appropriate threshold value for distinguishing LoS and NLoS in lower heights, which is also reported in [15]. To investigate further, we collected a set of measurements in NLoS when we place a metal plate of 1 in thickness as an obstacle between two feet. The results are shown in Fig. 5. As it can be learned from the top view of data, there is a positive bias in the UWB range measurement under NLoS conditions compared to LoS conditions. Once the NLoS is identified, the bias can be removed manually. However, the LoS and NLoS UWB PM measurements are not separable with merely a fixed deterministic threshold according to the 3-D plot. Therefore, our results conclude that a power-based identification based on a fixed PM threshold is not an appropriate measure to identify NLoS measurements at lower heights.

Table 1 – The UWB range measurements RMSE in different orientations.

Angle (°)	0	45	90	135	180	225	270	315
RMSE (in)	3.0	5.5	2.3	4.9	6.6	7.6	1.7	2.4

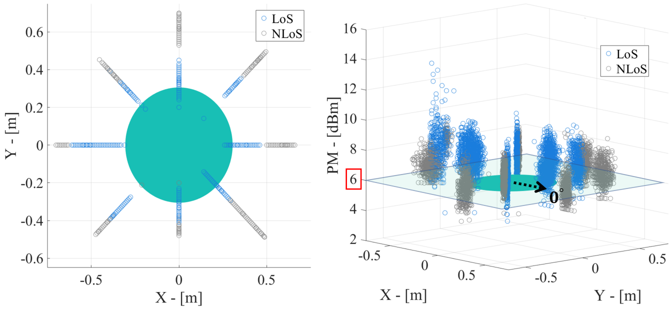


Fig. 5 – The UWB measurements under LoS and NLoS conditions.

C. UWB placement effect on localization accuracy

To investigate the effect of UWB sensor placement on localization accuracy of a dual-foot mounted ZUPT-aided INS, we carried out a set of experiments in which a pedestrian walked on a straight line of length 43.5 m, as shown in Fig. 6. The experiments were conducted in the Engineering Gateway Building at the University of California, Irvine, using the Lab-on-Shoe platform (Fig. 1) whose foot-mounted UWB sensors were at 6.0 in height from the ground in four different configuration shown in Fig. 7. In this setting, there is always a clear path between the two feet, which ensures the LoS condition throughout the experiments. The sampling rates of the IMU and the UWB sensor were set to 1000 Hz and 10 Hz, respectively. Comparing with sensors placement discussed in Section II-B, configuration 1 to 4 corresponds to a relative orientation of 180°, 90°, 0° and 270° between the sensors. We carried out five sets of walks along straight reference trajectory for each configuration. The results of these experiments are shown in Fig. 8, which presents the localized trajectories, and Fig. 9, which shows the CEPs. The CEP is a measure of precision defined as the median error radius of a circle centered on the true value (the endpoint location in our experiments). As we can conclude from these plots, configuration 4 with CEP of 0.41% of the distance traveled compared to 0.42%, 1.07% and 0.85% of the distance traveled, respectively for configurations 1, 2 and 3, demonstrates the best localization performance. This result is consistent with what we concluded in Section II-B, which indicated the relative orientation of 270° is the optimal configuration when the sensors are placed stationary and the pedestrian stands still with feet parallel. The reader should note that for all four configurations the CEP value reported in Fig. 9 normalized by the distance traveled is significantly less than the CEP values of 6.90% and 4.64% of the distance traveled reported in [5] (a walk over a straight line of 53 m) for, respectively, ZUPT aided by ultrasonic foot-to-foot ranging and ZUPT aided by vision-based foot-to-foot ranging.

III. CONCLUSIONS

This letter investigated effect of the UWB sensor placement for foot-to-foot ranging in dual-foot mounted ZUPT-aided pedestrian

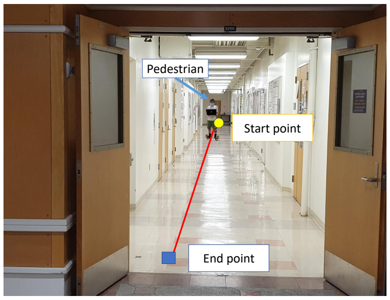


Fig. 6 – The ZUPT-aided pedestrian inertial navigation experiment.

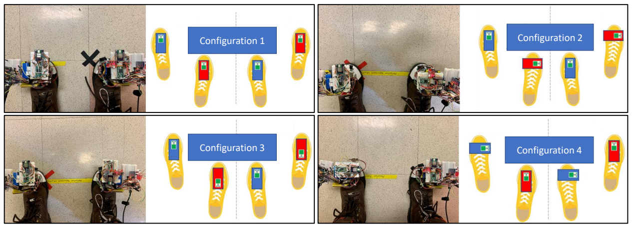


Fig. 7 – Four different UWB sensor placement configurations.

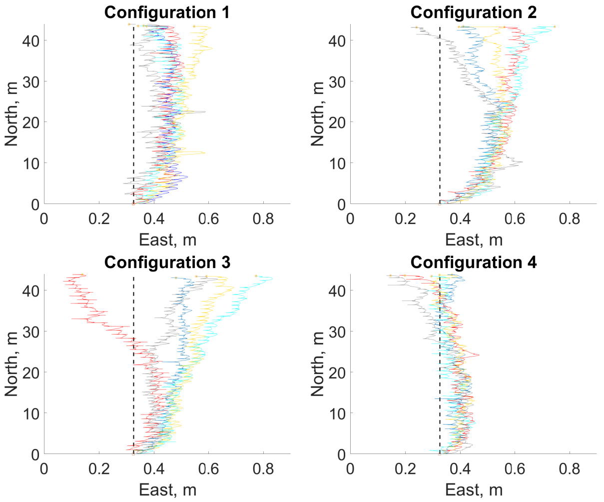


Fig. 8 – The estimated trajectories of the right foot in four configurations. The black dashed line represents the reference trajectory. The red, yellow, light blue, dark blue and gray lines denote the walks 1 to 5, respectively.

inertial navigation. The paper discussed the factors affecting the UWB measurements, including the height from the ground and the relative orientation of the UWB sensors. The result showed that the UWB orientation significantly influences the measurement quality. The height also impacts the measurements significantly in lower heights due to the ground effect. In a set of experimental studies, the paper investigated the best placement for the UWB sensors and derived a preferable configuration in the ZUPT-aided pedestrian inertial navigation. Our results also illustrated that the well-known power-based NLoS discriminator that uses a fixed power metric threshold to identify NLoS UWB range measurements is not an appropriate measure at low heights.

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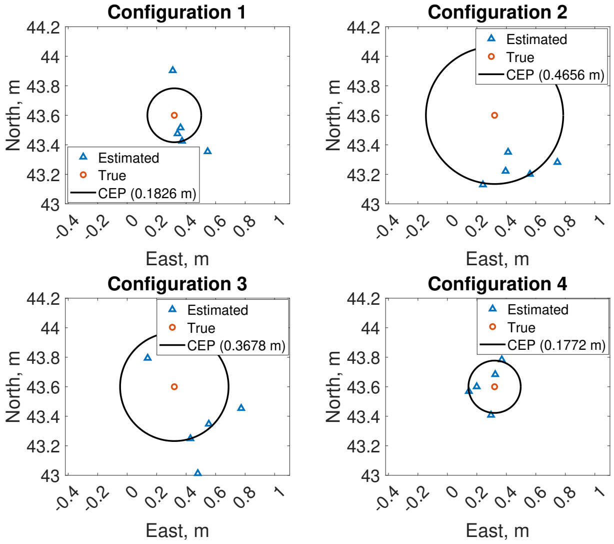

Fig. 9 – The CEP for four configurations.

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