A Tightly-Coupled UWB/INS Integration with Forward-Backward Data Fusion

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Outline

1. Introduction
2. Algorithm Formulation
3. Develop of Prototype
4. Experiment Results
5. Conclusions

Outdoor Environments

GNSS

Onboard sensors

Inertial Measurement Unit (IMU)

- **3D accelerometer**
- **3D gyroscope**
- **3D magnetometer**

In outdoor environments, GNSS/INS has been widely used for precise positioning and navigation.

1. Introduction

Indoor Environments

Intelligent mobile robots

Unmanned Aerial Vehicle

Applications
- Mapping
- Exploration
- Search and rescue
- Transportation

Requirements
- Robust and accurate positioning
- Location under any circumstance

Existing Indoor Positioning Techniques

WiFi Bluetooth ZigBee RFID PDR

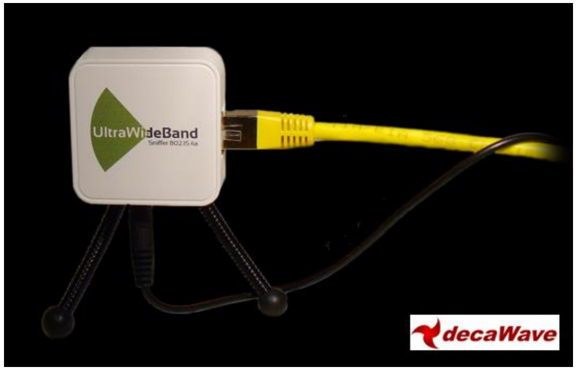
- Limited Positioning accuracy (several meters)
- Easily be affected

1. Introduction

Challenges

Accurate position estimation will be the key.

Not available in indoor environments



Ultra-Wideband (UWB) can provide high accuracy positioning results (cm~dm level)

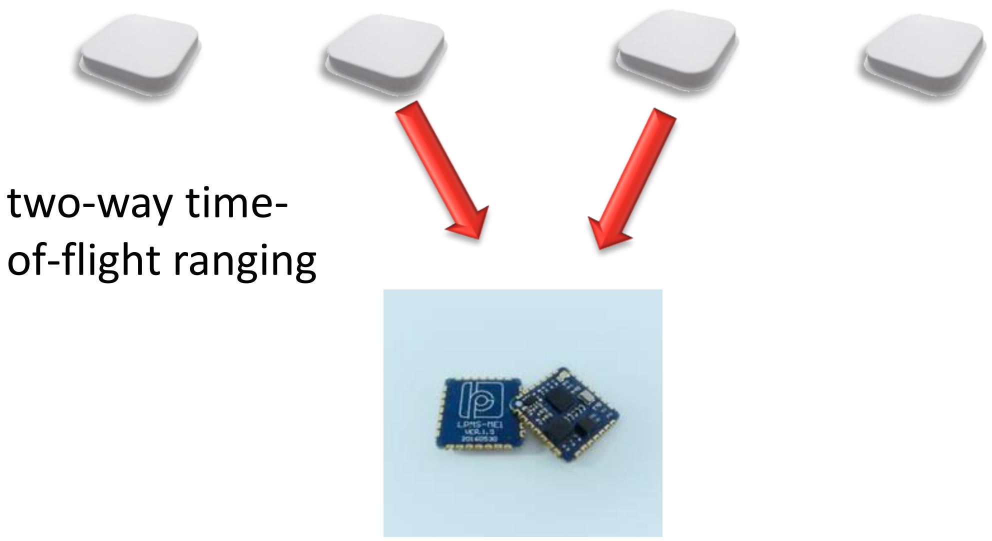
High price and high weight

MEMS IMU: Low cost and Low weight

UWB/MEMS integration

1. Introduction

Integration Strategies



- **Loose Couple: UWB position + IMU**

Disadvantage: at least 3 anchors are needed for UWB positioning.

- **Tight Couple: UWB ranges + IMU**

Advantage: available when UWB signal is blocked by obstacles.

Objectives: integrating UWB and low cost IMU to provide high accuracy positioning estimate.

2. Algorithm Formulation

UWB/INS tightly coupled integration

INS mechanization

$$\boldsymbol{\omega}_{ie}^{n} = [\omega_{ie}\cos L \quad 0 \quad -\omega_{ie}\sin L]$$

$$\boldsymbol{\omega}_{en}^{n} = \left[\frac{v_E^n}{R_N+h} \quad -\frac{v_N^n}{R_M+h} \quad -\frac{v_E^n \tan L}{R_N+h}\right]$$

can be neglected for MEMS and low-dynamics applications

$$\dot{\boldsymbol{v}}^n = \boldsymbol{f}^n - \left(2\boldsymbol{\omega}_{ie}^n + \boldsymbol{\omega}_{en}^n\right) \times \boldsymbol{v}^n + \boldsymbol{g}_l^n$$

$$\dot{\boldsymbol{C}}_b^n = \boldsymbol{C}_b^n \boldsymbol{\Omega}_{nb}^b = \boldsymbol{C}_b^n \left(\boldsymbol{\Omega}_{ib}^b - \boldsymbol{\Omega}_{in}^b\right)$$

For GNSS/INS integration in the navigation frame

$$\dot{\boldsymbol{v}}^n = \boldsymbol{f}^n + \boldsymbol{g}_l^n$$

$$\dot{\boldsymbol{C}}_b^n = \boldsymbol{C}_b^n \boldsymbol{\Omega}_{nb}^b = \boldsymbol{C}_b^n \left(\boldsymbol{\Omega}_{ib}^b\right)$$

For UWB/MEMS integration in the indoor frame

INS error model

$$\delta\dot{\mathbf{v}} = -\delta\psi \times \boldsymbol{f} + \nabla$$

$$\delta\dot{\mathbf{r}} = \delta\mathbf{v}$$

$$\delta\dot{\psi} = \varepsilon$$

Error states

$$\begin{cases} \mathbf{x}_{Nav} = [\delta r_x, \delta r_y, \delta r_z, \delta v_x, \delta v_y, \delta v_z, \delta\psi_x, \delta\psi_y, \delta\psi_z]^T \\ \mathbf{x}_{Acc} = [\nabla_{bx}, \nabla_{by}, \nabla_{bz}, \nabla_{fx}, \nabla_{fy}, \nabla_{fz}]^T \\ \mathbf{x}_{Gyro} = [\varepsilon_{bx}, \varepsilon_{by}, \varepsilon_{bz}, \varepsilon_{fx}, \varepsilon_{fy}, \varepsilon_{fz}]^T \end{cases}$$

2. Algorithm Formulation

UWB/INS tightly coupled integration

Measurement model

For the two-way time-of-flight ranging approach, the measurement model is composed of the range difference vector between UWB and the INS predicted value:

$$\boldsymbol{Z} = \begin{bmatrix} r_1^{\mathrm{UWB}} - r_1^{\mathrm{INS}} \\ r_2^{\mathrm{UWB}} - r_2^{\mathrm{INS}} \\ \vdots \\ r_i^{\mathrm{UWB}} - r_i^{\mathrm{INS}} \end{bmatrix}$$

where $r_i^{\mathrm{UWB}} = \sqrt{\left(x^{\mathrm{UWB}} - x\right)^2 + \left(y^{\mathrm{UWB}} - y\right)^2 + \left(z^{\mathrm{UWB}} - z\right)^2}$

$$\boldsymbol{Z}_k = \boldsymbol{H}_k \boldsymbol{X}_k + \boldsymbol{\tau}$$

Extended Kalman filter (EKF) is used to fuse UWB and IMU observation, INS estimated navigation states are used to predict the UWB-observables within the EKF

Forward and backward integration

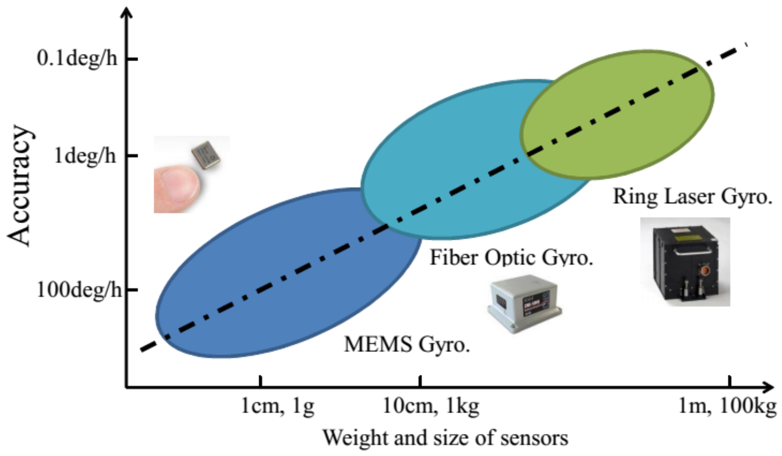
Initialization problem

Position: UWB positioning result ;

Velocity: Static start;

Attitude: pitch and roll are determined with accelerometer data;

Heading (yaw) angle cannot be directly measured in the local navigation frame for MEMS.



Inaccurate initial attitude requires a long period to converge.

2. Algorithm Formulation

Forward and backward integration

Normal INS resolution

$$\dot{C}_b^l = C_b^l\left(\omega_{ib}^b \times\right)$$

$$\dot{v}^l = C_b^l f_b + g^l$$

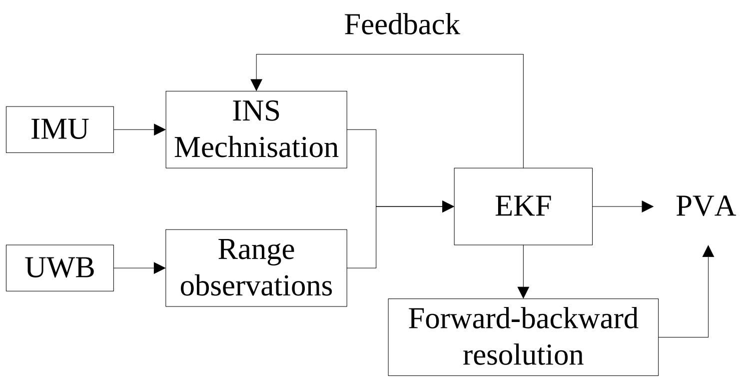
$$\dot{r}^l = v^l$$

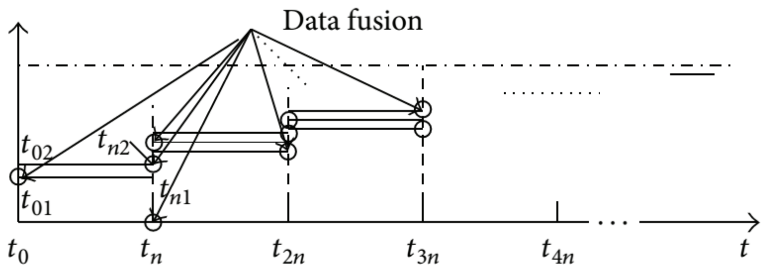
Reverse INS resolution

$$\dot{C}_b^l = C_b^l\left(-\omega_{ib}^b \times\right)$$

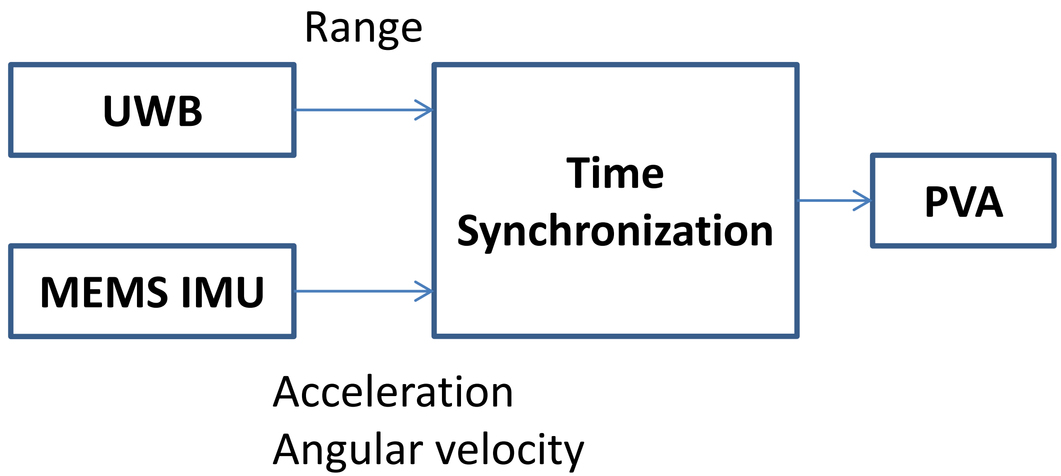
$$\dot{v}^l = -C_b^l f_b + g^l$$

$$\dot{r}^l = -v^l$$



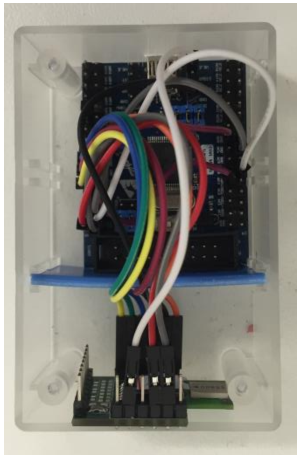


3. Develop of Prototype



Feature of Prototype	
Components	5 UWB Anchors 1 UWB Tag + MEMS IMU (accelerometer & Gyro) Time Synchronization
Size & Shape	UWB 23mmx13mm

Tag



Anchor

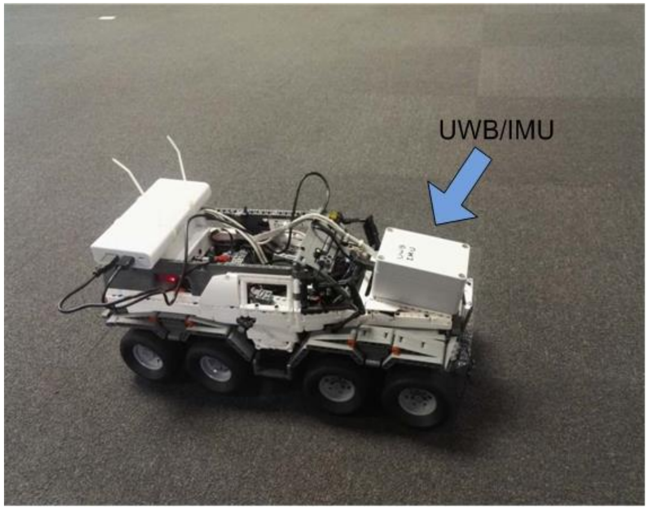
4. Experiment Results

Experimental description

Site： Old Main Building, UNSW
Date: November 2, 2017
Equipment: UWB (developed based on Decawave DWM1000) , 5 Hz; IMU (LPMS-ME1), 100 Hz rate.

In dynamic test, the vehicle moved along the marked trajectory as close as possible

Test environment

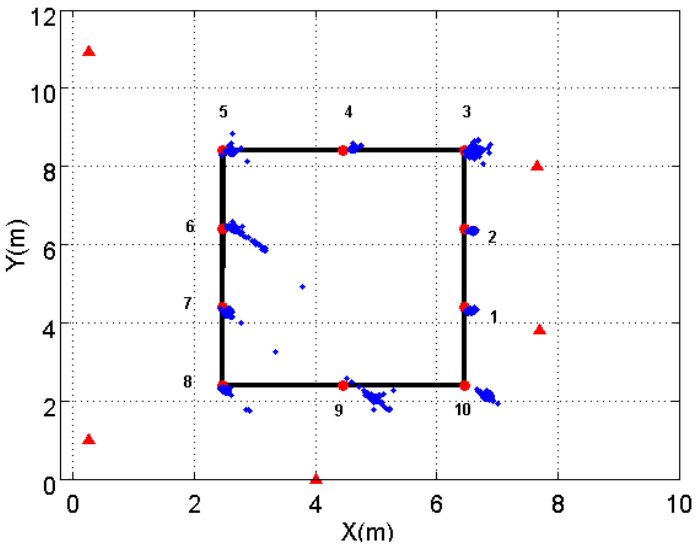


Test equipment

4. Experiment Results

UWB static positioning results

- A total of ten test points were evenly selected in the test area;
- Positioning errors for most test points are smaller than 0.2 m for each component;
- Large positioning errors can be observed at the test points 6, 9 and 10, which may be caused by signal blockage.



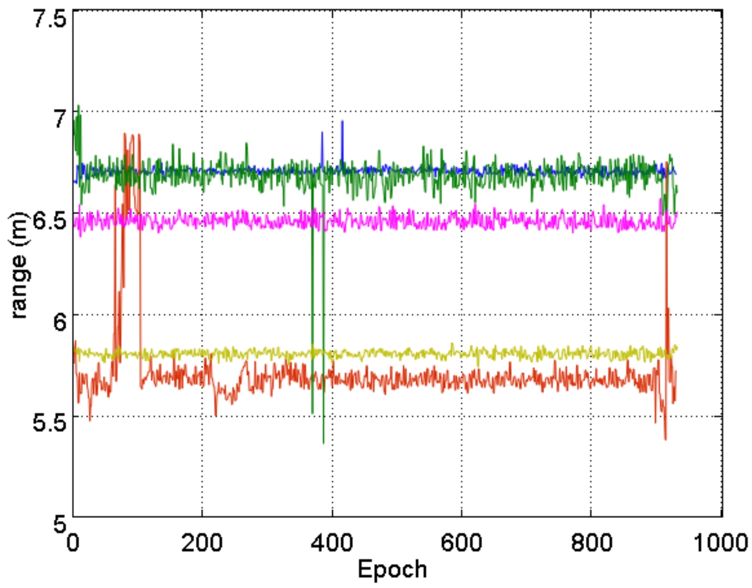
Static positioning

Test point	RMS (m)		MAX (m)	
	X	Y	X	Y
1	0.104	0.102	0.214	0.165
2	0.143	0.054	0.204	0.121
3	0.176	0.061	0.425	0.340
4	0.166	0.063	0.300	0.179
5	0.154	0.054	0.400	0.429
6	0.240	0.099	1.320	1.495
7	0.085	0.188	0.876	1.143
8	0.052	0.131	0.462	0.648
9	0.508	0.332	0.821	0.639
10	0.391	0.303	0.557	0.473
Mean	0.202	0.139	0.558	0.563

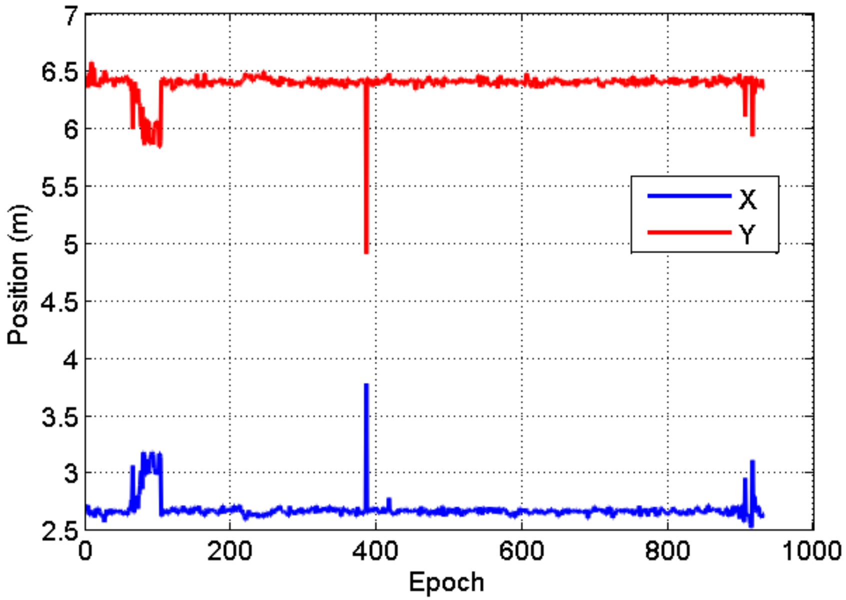
4. Experiment Results

UWB static positioning results

- At test point 6, there were about 7 s (35 measurements) abnormal in the beginning period.
- The range observations from Anchor 2 (0.25,10.94) were evidently biased.



Range observations



Positioning results

Test point 6

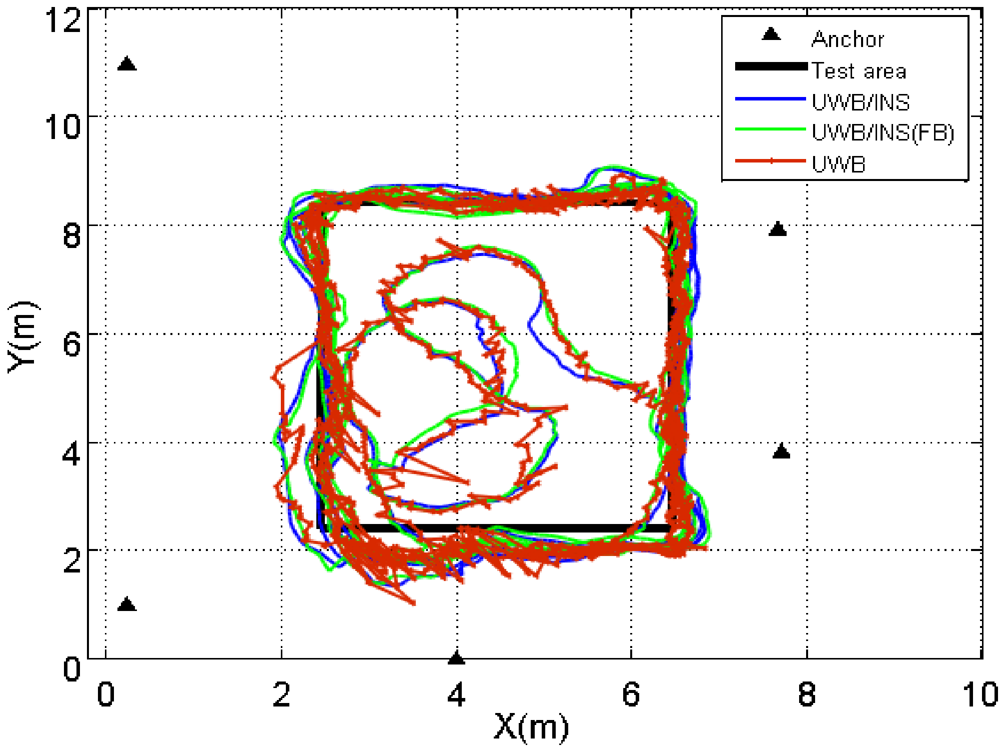
UWB/INS integration results

- The test vehicle pointed approximately to Y-axis during the stationary period, than conducted a "8" shape dynamic alignment;
- Three processing schemes :

(1) UWB positioning;

(2) UWB/INS tightly coupled integration;

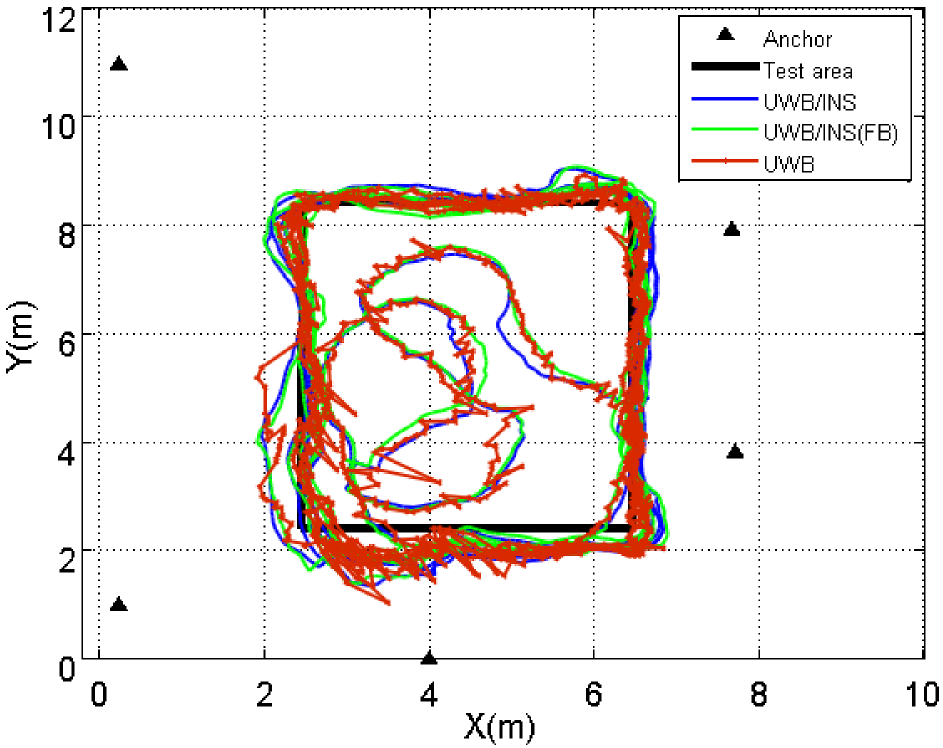
(3) UWB/INS tightly coupled integration with forward-backward resolution.



4. Experiment Results

UWB/INS integration results

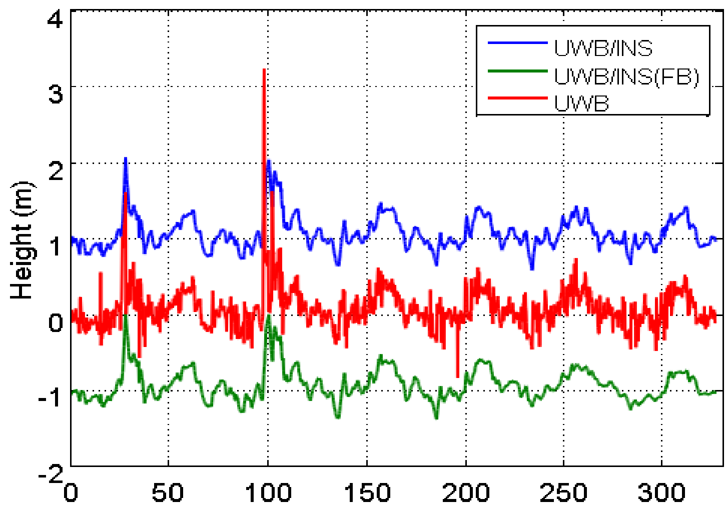
- UWB/INS integration system can provide superior positioning performance compared to UWB alone;
- The integrated system can provide more robust and smoother positioning results;
- By applying the repeated resolution scheme, the improved positioning performance can be observed, especially when initial heading information is not accurate for the low-cost IMU.



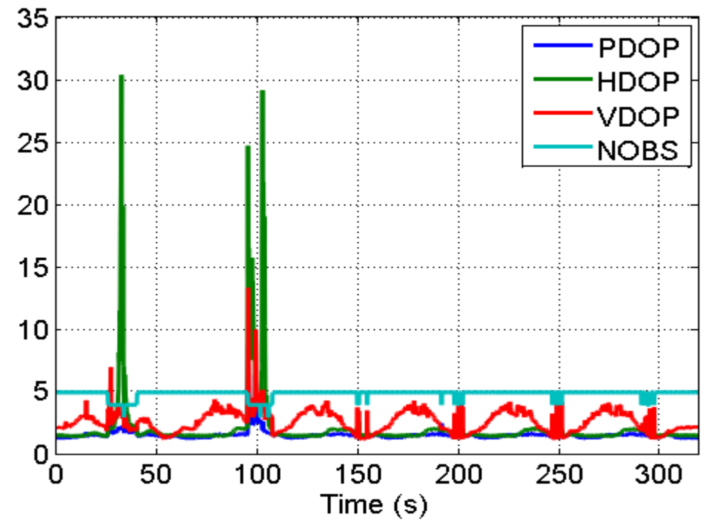
4. Experiment Results

UWB/INS integration results

- The standard deviations (STD) for three schemes are 0.256 m, 0.214 m and 0.207 m.
- Max height difference are 3.148 m, 1.053 m and 0.960 m.
- The height variations are mainly affected by UWB geometric variations.



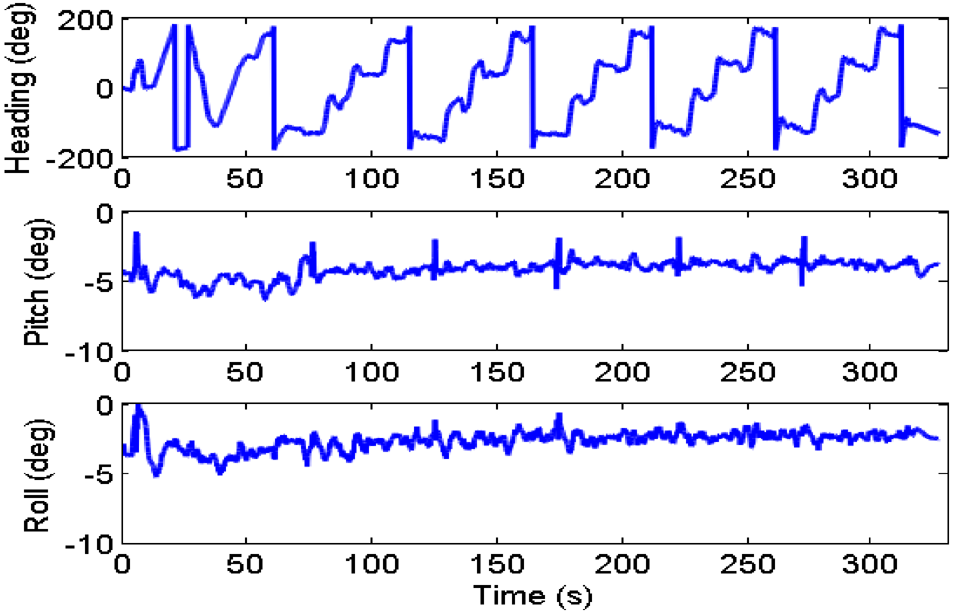
Height estimates



DOP value

UWB/INS integration results

- The heading angle changed periodically during the movement, while the pitch angle and roll angle remained steady without large changes.



Estimated attitude angles

5. Conclusions

- A tightly coupled indoor positioning system which combines UWB and INS is proposed.
- A forward-backward data fusion is proposed to improve the navigation performance.
- The static horizontal positioning errors of UWB positioning system is less than 0.2 m under the benign conditions.
- The UWB/INS integration system can provide superior positioning performance compared to UWB positioning alone.
- The added repeated resolution can improve the initial positioning performance for the low cost MEMS IMU.

Thank you for your attention