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
1. Introduction

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

- Applications
  - Mapping
  - Exploration
  - Search and rescue
  - Transportation

- Requirements
  - Robust and accurate positioning
  - Location under any circumstance

Intelligent mobile robots

Unmanned Aerial Vehicle

Existing Indoor Positioning Techniques

- Limited Positioning accuracy (several meters)
- Easily be affected
1. Introduction

Challenges

Accurate position estimation will be the key.

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

MEMS IMU: Low cost and Low weight

UWB/MEMS integration

Not available in indoor environments

High price and high weight
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

\[ \dot{v}^n = f^n - \left(2\omega_{ie}^n + \omega_{en}^n\right) \times v^n + g^n_l \]

\[ \dot{C}_b^n = C_b^n \Omega_{nb}^b = C_b^n \left( \Omega_{ib}^b - \Omega_{in}^b \right) \]

For GNSS/INS integration in the navigation frame

\[ \delta \dot{v} = -\delta \psi \times f + \nabla \]

INS error model

\[ \delta \dot{r} = \delta v \]

\[ \delta \psi = \epsilon \]

\[ \omega_{ie}^n = \begin{bmatrix} \omega_{ie} \cos L & 0 & -\omega_{ie} \sin L \end{bmatrix} \]

\[ \omega_{en}^n = \begin{bmatrix} \frac{v_E^n}{R_N + h} & -\frac{v_N^n}{R_M + h} & -\frac{v_E^n \tan L}{R_N + h} \end{bmatrix} \]

can be neglected for MEMS and low-dynamics applications

\[ \dot{v}^n = f^n + g^n_l \]

\[ \dot{C}_b^n = C_b^n \Omega_{nb}^b = C_b^n \left( \Omega_{ib}^b \right) \]

For UWB/MEMS integration in the indoor frame

Error states

\[ \begin{align*}
\mathbf{x}_{Nav} &= [\delta r_x, \delta r_y, \delta r_z, \delta v_x, \delta v_y, \delta v_z, \delta \psi_x, \delta \psi_y, \delta \psi_z]^T \\
\mathbf{x}_{Acc} &= [\nabla b_x, \nabla b_y, \nabla b_z, \nabla f_x, \nabla f_y, \nabla f_z]^T \\
\mathbf{x}_{Gyro} &= [\epsilon b_x, \epsilon b_y, \epsilon b_z, \epsilon f_x, \epsilon f_y, \epsilon f_z]^T
\end{align*} \]
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:

\[
Z = \begin{bmatrix}
    r_{1}^{\text{UWB}} - r_{1}^{\text{INS}} \\
    r_{2}^{\text{UWB}} - r_{2}^{\text{INS}} \\
    \vdots \\
    r_{i}^{\text{UWB}} - r_{i}^{\text{INS}}
\end{bmatrix}
\]

where

\[
r_{i}^{\text{UWB}} = \sqrt{(x_{\text{UWB}} - x)^2 + (y_{\text{UWB}} - y)^2 + (z_{\text{UWB}} - z)^2}
\]

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.
2. Algorithm Formulation

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

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

\[
\dot{\mathbf{v}}^l = C_b^l f_b + g^l
\]

\[
\mathbf{r}^l = \mathbf{v}^l
\]

Reverse INS resolution

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

\[
\dot{\mathbf{v}}^l = -C_b^l f_b + g^l
\]

\[
\mathbf{r}^l = -\mathbf{v}^l
\]
3. Develop of Prototype

**Feature of Prototype**

<table>
<thead>
<tr>
<th>Components</th>
<th>5 UWB Anchors 1 UWB Tag + MEMS IMU (accelerometer &amp; Gyro) Time Synchronization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size &amp; Shape</td>
<td>UWB 23mmx13mm</td>
</tr>
</tbody>
</table>

**Diagram:**

- **UWB**
- **MEMS IMU**
  - Range
  - Time Synchronization
  - PVA
  - Acceleration
  - Angular velocity

**Components:**

- 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.
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.

<table>
<thead>
<tr>
<th>Test point</th>
<th>RMS (m)</th>
<th>MAX (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>1</td>
<td>0.104</td>
<td>0.102</td>
</tr>
<tr>
<td>2</td>
<td>0.143</td>
<td>0.054</td>
</tr>
<tr>
<td>3</td>
<td>0.176</td>
<td>0.061</td>
</tr>
<tr>
<td>4</td>
<td>0.166</td>
<td>0.063</td>
</tr>
<tr>
<td>5</td>
<td>0.154</td>
<td>0.054</td>
</tr>
<tr>
<td>6</td>
<td>0.240</td>
<td>0.099</td>
</tr>
<tr>
<td>7</td>
<td>0.085</td>
<td>0.188</td>
</tr>
<tr>
<td>8</td>
<td>0.052</td>
<td>0.131</td>
</tr>
<tr>
<td>9</td>
<td>0.508</td>
<td>0.332</td>
</tr>
<tr>
<td>10</td>
<td>0.391</td>
<td>0.303</td>
</tr>
<tr>
<td>Mean</td>
<td>0.202</td>
<td>0.139</td>
</tr>
</tbody>
</table>
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.
4. Experiment Results

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