Twin IMU-HSGPS Integration for Pedestrian Navigation

Jared Bancroft

Position, Location And Navigation (PLAN) Group
Department of Geomatics Engineering
University of Calgary

Alberta ION Chapter Meeting
3rd Oct 2008
Pedestrian Navigation Applications

- Locate personnel in any conditions
  - Military applications
  - Fire fighting, police force and emergency services
  - Navigation in urban areas
  - Location Based Services (LBS)

- Typical Environments
  - Forest canopy
  - Urban canyons
  - Indoors
  - Underground parkades
Why Use 2 IMUs?

- Because 2 is better than 1!
- Better accuracy in GPS limited areas
- Improving availability for users
- Improving reliability for users
- In the event of an IMU failing or temporary data outages, the system can operate in a single IMU configuration
Review of Single IMU Integration

- **29-state filter**
  - Position, Velocity, Attitude (9)
  - Accelerometer and Gyro
    - **Biases** (Gauss Markov) (6)
    - **Scale Factor** (Gauss Markov) (6)
    - **Turn on Biases** (Random Constant) (6)
      - GPS Clock Errors (2)
  - Tight integration approach
  - Zero Velocity Updates (ZUPT) performed when foot is at rest during gait cycle
  - GPS observations weighted using C/N₀ ratio
Stance Phase Detection

Twin IMU Integration Scheme

- **IMU**
  - **Corrections**
  - **INS Mechanization**
    - **Predicted Range & Doppler**
    - **Ephemeris**
  - **GPS**
- **Error Estimates**
  - **Corrections**
  - **INS Mechanization**
    - **Predicted Range & Doppler**
  - **GPS/INS Kalman Filter**
- **Output**
  - **Zero-Velocity Update**
  - **Relative Update**
Twin IMU Integration

- Two single IMU filters are stacked to form a larger twin IMU filter – **a 56-state model**
- Each block within the filter (for each IMU) contains its own set of states, transition matrix, design matrix, covariance matrices, etc.
- The twin filter can be accessed as a unit, or individually, as necessary

**Prediction Cycle**
\[
\begin{bmatrix}
\partial x_{k+1}^1 \\
\partial x_{k+1}^2
\end{bmatrix} = \begin{bmatrix}
\Phi_{k,k+1}^1 & 0 \\
0 & \Phi_{k,k+1}^2
\end{bmatrix} \begin{bmatrix}
\partial x_k^1 \\
\partial x_k^2
\end{bmatrix} + \begin{bmatrix}
w_{k}^1 \\
w_k^2
\end{bmatrix}
\]

**System Dynamic Model**
\[
\dot{x}(t) = F(t)x(t) + G(t)w(t)
\]

**Update Cycle**
\[
\begin{bmatrix}
\partial z_{k+1}^1 \\
\partial z_{k+1}^2
\end{bmatrix} = \begin{bmatrix}
H_{k+1}^1 & 0 \\
0 & H_{k+1}^2
\end{bmatrix} \begin{bmatrix}
\partial x_{k+1}^1 \\
\partial x_{k+1}^2
\end{bmatrix} + \begin{bmatrix}
\eta_{k+1}^1 \\
\eta_{k+1}^2
\end{bmatrix}
\]

**System Observation Model**
\[
z(t) = H(t)x(t) + \eta(t)
\]
Twin IMU Relative Position Updates

- **Relative Vector Update (RVUPT)**
  - Uses the vector between the feet
  - Observations derived from integrated step length \( y \), approximate width between feet \( x \), and assumed zero elevation difference between feet \( z \)

- **Relative Distance Update (RDUUPT)**
  - Uses the magnitude of the relative vector \( r \)
Relative Vector Updates (RVUPT)

- The observations are the vector between the feet derived from the step length
- The rear foot, which is just about to enter the heel off stage forms the local frame
- The relative vector is rotated into the ECEF frame via a rotation matrix
  - The weakness of this update lies in the error of the rotation matrix, in particularly the heading error

\[
\left( \hat{r}_{IMU_1} - \hat{r}_{IMU_2} \right)_{3 \times 1} - \hat{\delta r}_{3 \times 1} = \begin{bmatrix} I_{3 \times 3} & 0_{3 \times 24} & -I_{3 \times 3} & 0_{3 \times 24} & 0_{3 \times 2} \end{bmatrix} \hat{\delta \bar{x}} + \eta_{\delta r} \\
= H \hat{\delta \bar{x}} + \eta_{\delta x}
\]
Test Data Collected

- A tactical grade IMU was used to provide a reference solution (NovAtel OEM4 + HG1700 1 deg/hr IMU)
  - Processed with RTS Smoothing to provide < 6 m 3D (1σ) accuracy indoors
- HSGPS (SirfStarIII Receiver) @ 1 Hz
- MEMS IMU (x2) (Cloud Cap Technology’s Crista) @ 100 Hz

**IMU Specifications**

- 2 deg/s Gyro bias
- 0.2 m/s² Accelerometer bias
Trajectory of Data Collection

High multipath from building

Added noise from green leaved trees

Green leaved trees reducing observability

Walking in bushes

Extreme multipath in building with low $C/N_0$
Satellite Observability and Signal Strength

Outside Data
- Outside under leaved trees, receiver continuously tracked more than 9 satellites
- Average $C/N_0$ outside is 41 dB-Hz, with occasional intervals ranging 35 - 39

Indoor Data – 2 Loops

<table>
<thead>
<tr>
<th></th>
<th>Loop 1</th>
<th>Loop 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoors</td>
<td>172 s</td>
<td>245 s</td>
</tr>
<tr>
<td>Satellites Tracked</td>
<td>0 - 8</td>
<td>0 - 8</td>
</tr>
<tr>
<td>Complete Outages</td>
<td>53 s</td>
<td>62 s</td>
</tr>
<tr>
<td>$C/No$ (dB-Hz)</td>
<td>10 - 27</td>
<td>10 - 29</td>
</tr>
</tbody>
</table>
**GPS Only Navigation Solution**

### Outside Data
- HSGPS compares very closely with reference trajectory
- 1.6 m mean horizontal error
  - 1.7 m RMS
- 1.0 m mean vertical error
  - 1.2 m RMS

### Indoor Data
- An erroneous solution

<table>
<thead>
<tr>
<th></th>
<th>Indoor (172 s)</th>
<th>Indoor (245 s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Hz Error (m)</td>
<td>68.3</td>
<td>65.5</td>
</tr>
<tr>
<td>RMS Hz Error (m)</td>
<td>98.3</td>
<td>93.9</td>
</tr>
<tr>
<td>Mean Vt Error (m)</td>
<td>15.1</td>
<td>8.2</td>
</tr>
<tr>
<td>RMS Vert Error (m)</td>
<td>16.5</td>
<td>13.8</td>
</tr>
</tbody>
</table>
Twin IMU Navigation Solution

**Outside Data**
- Twin IMU follows the GPS solution and provides similar results to that of a GPS only filtered solution.

**Inside Data**
- Different processing strategies provide different results, RDUPT providing the lowest error.
- Second time around loop errors increase.
Twin IMU Navigation Error

<table>
<thead>
<tr>
<th>Processing Strategy</th>
<th>Loop 1</th>
<th>Loop 2</th>
<th>Loop 3</th>
<th>Improvement Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>RDUP T</td>
<td>15</td>
<td>19</td>
<td>32</td>
<td>3.5</td>
</tr>
<tr>
<td>RVUP T</td>
<td>50</td>
<td>39</td>
<td>38</td>
<td>2.9</td>
</tr>
<tr>
<td>Single IMU</td>
<td>40</td>
<td>80</td>
<td>120</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Correlation of Single IMU

Correlation Coefficient of Covariance Matrix
Duration: 0.0 s

Correlation Coefficient

Pos | Vel | Att | GyroBias | AccBias | AccSF | GyroSF | AccTOB | GyroTOB | Rx Clock
---|-----|-----|----------|---------|-------|--------|--------|---------|---------
Pos |     |     |          |         |       |        |        |         |         |
Vel |     |     |          |         |       |        |        |         |         |
Att |     |     |          |         |       |        |        |         |         |
GyroBias |     |     |          |         |       |        |        |         |         |
AccBias |     |     |          |         |       |        |        |         |         |
AccSF |     |     |          |         |       |        |        |         |         |
GyroSF |     |     |          |         |       |        |        |         |         |
AccTOB |     |     |          |         |       |        |        |         |         |
GyroTOB |     |     |          |         |       |        |        |         |         |
Rx Clock |     |     |          |         |       |        |        |         |         |
Correlation of RDUPT Twin IMU

Correlation Coefficient of Twin RDUPT Covariance Matrix
Duration: 1.0 s
Conclusions

- Implementing a twin IMU filter for pedestrian navigation was shown to improve navigation in GPS reduced areas by a factor of 2.9 - 3.5.

- Two methods were used to relate the IMUs' relative position and provide an update to the filter:
  - Relative distance (RDUPT)
  - Relative vector (RVUPT)

- Correlation induced from relative updates between IMUs is negligible.