Performance Analysis of Loosely Coupled RTK-GNSS/IMU/Vehicle Speed Sensors in Urban Environment

Ren Kikuchi, Nobuaki Kubo (TUMSAT)
Shigeki Kawai, Ichiro Kato, Nobuyuki Taguchi (DENSO corporation)

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Background

- Recently, advanced driver assistance systems with features such as lane change assist and automatic braking in automotive applications have experienced a rapid growth.
- For a more advanced operating system implementation, improvement of the vehicle location accuracy is desired. Positioning by GNSS is becoming a widely used method for this purpose where accurate positioning at a few cm-level can be obtained by using Real-Time Kinematic (RTK) technique.
Background

- the use of RTK-GNSS
  - For precise survey
  - For mapping

- What’s the performance of the RTK-GNSS in urban environments?
- The possibility of accuracy improvement technique using integrating GNSS and vehicle sensors.
Objective

The position measurement with large errors over several meters can not be avoided

Multipath, DOP, and wrong FIX etc. GNSS signal outage

1. How to integrate the RTK-GNSS, IMU, and vehicle sensors in an effective way
2. What benefits the integration will yield

TARGET: Maximum horizontal error < 1.5m
Algorithm of Integration

- Accelerometer
- Vehicle Sensor
- Gyroscope
- GNSS Raw Data (+SQC)

- Speed
- Yaw Rate
- Velocity
- Heading

- Movement Detection
- Globe Position
- Float Position

- Heading Filter
- Velocity Filter
- RTK-GNSS
- Wrong Fix Detection

- #1
- #2
- #3

*SQT: Signal Quality Check

# : Order of Priority
Position from RTK-GNSS

- Double-differenced observations in each satellite system
- Signal quality check and ADOP
- Doppler aided LAMBDA method
- Ratio Test

GPS/QZS+BDS

GNSS Observables
Double-difference
Least-squares Float Solution
AR using Integer LS
Ratio test
Wrong Fix Detection
Position from RTK-GNSS

- Ambiguity Resolution
  - LAMBDA method
    - used to resolve Integer ambiguities
    - the ambiguities are resolved in a single epoch
  - Ratio Test
    - used to validate that the resulting ambiguities are correct
    - the threshold for the ratio test is set 3

- The value of Ratio test $\geq 3$  Fix solution
Wrong FIX Detection

- Calculate the change of the altitude

\[ \Delta h = \int_{t_1}^{t_2} v \sin(\theta) dt \]

- \( \theta \) is the pitch angle change deduced from a pitch rate gyro

- Epochs of \( t_1 \) and \( t_2 \) are only used when the RTK-GNSS is available

Wrong Fix \( \rightarrow \) Over 1m
Velocity from GNSS

- Relative velocity → **Doppler shift** (Doppler frequency)
- Ephemeris information → satellite velocity
- Velocity of the vehicle can be calculated as follows

\[ \Delta f = \frac{f \rho'}{c} \]

\[ (V_i - V)S_i + \Delta \rho = \rho_i \]

- \( f \): the frequency of the carrier from GPS
- \( \Delta f \): the frequency shift from the Doppler measurement
- \( c \): the speed of light
- \( \rho \): the relative speed between the satellite and the vehicle
- \( V_i \): the velocity of the satellite
- \( V \): the velocity of the vehicle
- \( S_i \): the eye vector of the satellite
- \( \Delta \rho \): the error of the oscillator

\[
E_t = E_{t-1} + \frac{(V_{E_{t-1}} + V_{E_t})}{2} \Delta t
\]

\[
N_t = N_{t-1} + \frac{(V_{N_{t-1}} + V_{N_t})}{2} \Delta t
\]
Heading from GNSS velocity

- We can not get the right heading when the vehicle is stationary or in a low speed
  - GNSS velocity measurement has a few cm/s noise

- The heading error will increase when the vehicle is moving in a high yaw rate
  - GNSS sampling is in a low rate

- The data not satisfies the speed threshold or the DOP threshold will not be used
Heading Estimation Algorithm

- **Moving situations**  
  HDOP threshold : 2.5  
  - Low speed (below 0.5 m/s) (from vehicle speed sensors)  
  - Normal speed (over 0.5 m/s) with low yaw rate (below 4°/s)  
  - Normal speed with high yaw rate (over 4°/s)

- The measurement covariance will be updated in each state.

\[
x_k = (\psi_{g_k}, \omega_{g_k})
\]

\[
x_{k+1} = F_k x_k + G \omega_k
\]

\[
y_k = H x_k + v_k
\]

\[
\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k (y_k - H_k \hat{x}_{k|k-1})
\]

\[
\hat{x}_{k+1|k} = F_k \hat{x}_{k|k}
\]

\[
K_k = P_{k|k-1} H_k^T (H_k P_{k|k-1} H_k^T + R_k)^{-1}
\]

\[
P_{k|k} = P_{k|k-1} - K_k H_k P_{k|k-1}
\]

\[
P_{k+1|k} = F_k P_{k|k} F_k^T + G_k Q_k G_k^T
\]

\[
R = \begin{bmatrix}
\sigma^2_{\psi_o} & 0 \\
0 & \sigma^2_{\psi_t}
\end{bmatrix}
\]
DR(Estimated heading + Speed Sensors)

\[ E_t = E_{t-1} + \frac{(\cos(\theta_{t-1}) \ V_{t-1} + \cos(\theta_t) \ V_t)}{2} \Delta t \]

\[ N_t = N_{t-1} + \frac{(\sin(\theta_{t-1}) \ V_{t-1} + \sin(\theta_t) \ V_t)}{2} \Delta t \]
# Experiment

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>GNSS Antenna</td>
<td>NovAtel 703 GGG</td>
</tr>
<tr>
<td>GNSS Receiver</td>
<td>Trimble SPS 855</td>
</tr>
<tr>
<td>Baseline Length</td>
<td>- 10km</td>
</tr>
<tr>
<td>IMU</td>
<td>Analog Devices ADIS16445</td>
</tr>
<tr>
<td>Speed Sensor</td>
<td>Standard Vehicle Loaded Wheel Speed Sensors</td>
</tr>
<tr>
<td>Reference</td>
<td>POS/LV (Applanix) positional accuracy within 30 cm</td>
</tr>
<tr>
<td>Location</td>
<td>Nagoya City, Japan <em>(dense urban areas)</em></td>
</tr>
</tbody>
</table>
Experiment Course

Total 3 tests
Period: about 30min
Data rate: 10Hz

<table>
<thead>
<tr>
<th>Test</th>
<th>NUS (ave.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.2</td>
</tr>
<tr>
<td>2</td>
<td>9.7</td>
</tr>
<tr>
<td>3</td>
<td>9.3</td>
</tr>
</tbody>
</table>

Number of used satellites.
RTK-GNSS Performance

Max : 220.8 [s]  
800 [m]

+QZS and BDS increased the availability a lot.  
About 1.5-2 times compared with only GPS
Wrong FIX Detection Results

- Reference
- RTK.
- GNSS Vel.
- IMU

Google earth
Results of the Proposed Heading Estimation

<table>
<thead>
<tr>
<th></th>
<th>Test1</th>
<th>Test2</th>
<th>Test3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave. [deg]</td>
<td>0.09</td>
<td>-0.18</td>
<td>-0.05</td>
</tr>
<tr>
<td>RMSE [deg]</td>
<td>0.35</td>
<td>0.45</td>
<td>0.37</td>
</tr>
</tbody>
</table>
# Overall Results

<table>
<thead>
<tr>
<th>Method</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTK</td>
<td>57.4%</td>
</tr>
<tr>
<td>GNSS Vel.</td>
<td>16.3%</td>
</tr>
<tr>
<td>DR</td>
<td>26.2%</td>
</tr>
</tbody>
</table>

Max: 2.03 m

< 1.5m: 95.99%
Loosely coupled integration (RTK-GNSS/IMU/Speed sensors) method was proposed. RTK-GNSS has been improved by using multi-GNSS constellation. Wrong FIX detection was proposed and validated.

Good accuracy was maintained using a simple integration method. Loosely coupled KF was used to estimate important heading information.

Availability was improved to 100 %.
Percentage within 1.5 m horizontal was 91 – 95 %.
Maximum horizontal errors were reduced to 2 – 3 m.

<table>
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<th>Test3</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1.5m</td>
<td>Max</td>
<td>&lt;1.5m</td>
</tr>
<tr>
<td>95.99 %</td>
<td>2.03 m</td>
<td>91.77 %</td>
</tr>
</tbody>
</table>
Future Work

- Integrity monitoring
  Positioning by GNSS relays on weak signals that have well-known vulnerabilities and when being integrated with other systems, integrity and performance-based monitoring becomes an important task for protection from faults in order to produce robust precise position estimation. It is also important to alert the user in case that the system can not reach the target performance.
Thank you for your attention!
Signal Quality Test

Detect bad quality signal including multipath

Threshold

Minimum level