Integrity Monitoring for Reliable Positioning in Cooperative Intelligent Transport Systems

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Contents

- Why integrity monitoring?
- Integrated system for C-ITS.
- Our integrity monitoring approach.
- Models.
- Testing.
C-ITS

Cooperative Intelligent Transport Systems (C-ITS) deliver innovative services that will enable greater safety, savings in journey times, and reduced traffic congestion.
New technologies are likely be added to existing systems Industry may adapt V2X / Connected Vehicle technology as an add-on

Challenges unique to automotive

Design driven by styling, cost and complexity
Automotive design cycle is typically 3-4 years & design life is around 8 years*
Significant work is needed to widely utilize Over-the-Air (OTA) update capability
Concept of Operation **V2X** (V2V, V2I and V2P)

Concept of Operation

Vehicles broadcast absolute position & time Classify vehicles as: Traveling in same direction, opposite or other

Same lane or adjacent lane

- Identify threats & generate warnings

Typical accuracy requirements

- Road level: better than 5 m absolute
- Lane level: better than 1.5 m absolute

Objective

- Precise positioning is a fundamental component of ITS.
- We need to provide continuing, trustworthy and safe positioning.
- the system needs to have a full integrity monitoring.
Integrity Monitoring

Definitions:

- **Integrity** is that quality which relates to the trust which can be placed in the correctness of the information supplied by the total system.

- **Integrity** includes the ability of a system to provide timely warnings to the user when the system should not be used for the intended operation.

- **Integrity risk** is the probability of an undetected failure of the specified accuracy.

*What is difference between QC and IM?*

- IM generally implies a real-time application.
Integrity Monitoring

- Two main tasks:
  1. Detection and exclusion of faulty data (FDE).
  2. Check that system performance meets standards.

(Accuracy, reliability, continuity and integrity)
Positioning System (RTK /IMU/Speedometer)

A system capable of maintaining positioning during periods of GNSS blockage; e.g. urban environments or when passing through tunnels.
# Positioning continuity using RTK /IMU/speedometer

## Conditions

<table>
<thead>
<tr>
<th>Stream 1</th>
<th>Stream 2</th>
<th>Stream 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low-cost RTK</strong>&lt;br&gt;Provides cm accuracy</td>
<td><strong>Doppler</strong>&lt;br&gt;Err: sub-m to 1 m&lt;br&gt;update &lt; 1 min</td>
<td><strong>MEMS IMU/SS</strong>&lt;br&gt;Err: &lt; 2 m&lt;br&gt;Within 20 sec</td>
</tr>
</tbody>
</table>
| | • HDOP < 1.5;  
 • $|V_{GNSS} - V_{SS}| < 0.5$ m/s | **GNSS calibrate IMU**<br>• HDOP < 2.5  
 • $|V_{GNSS} - V_{SS}| < 1.5$ m/s  
 • $V_{SS} > 0.5$ m/s or ZUPT |

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[Note: The image contains a table and a diagram illustrating the positioning continuity using RTK, IMU, and speedometer streams.]
Observation models

A fault-free mode

\[ y = G \cdot x + b + \varepsilon \]

\( H_0 \) is: \( E\{y\} = G \cdot x + b, \quad D\{y\} = Q_y, \)

with faults

\[ y = G \cdot x + G_f \cdot \nabla + b + \varepsilon \]

\( H_a: \ E\{y\} = G \cdot x + G_f \cdot \nabla + b, \quad D\{y\} = Q_y \)

\[ 1 \leq q \leq df \]
Integrity monitoring

i. FDE

- **Detection of faulty observations**
  \[ \hat{e}^T Q^{-1}_y \hat{e} \geq \chi^2_\alpha(df_i, 0) \]

- **Exclusion of faulty observations**
  \[ |\hat{x} - \hat{x}_i| > T_i \]

Confirm exclusion
\[ \hat{e}^T A_i Q^{-1}_y \hat{e} \geq \chi^2_\alpha(df_i, 0) \]
\[ |w_j| \geq N_{\alpha}(0,1) \]
\[ |w_i| \geq |w_k| \quad \text{for } k=1 \text{ to } m \]

ii. Integrity checks

- **HPE < HPL**
- **HPL < HAL**
RTK integrity RISK

* \( P(|dx_H| \geq HPL) \geq P(I)_H \)

* \( P(|dx_V| \geq VPL) \geq P(I)_V \)

\[
P(I)_H = P(|dx_H|_o \geq HPL_o| CF) \times PCF \times P^{m_{d\mode1}} \\
+ P(|dx_H|_o \geq HPL_o| IF) \times PIF \times P^{m_{d\mode2}} \\
+ \sum_{i=1}^{m} P(|dx_H|_i \geq HPL_i| IF) \times PIF \times P^{m_{d\mode3}}
\]

Miss-detection

Mode 1: ambiguities are correctly fixed (\(PCF\)).
Mode 2: ambiguities are incorrectly fixed (\(PIF\)) using all sats
Mode 3: ambiguities are incorrectly fixed (\(PIF\)) excluding satellite \(i\).

\( PIF = 1 - PCF \)
RTK Protection Levels

• A new HPL metric: for the maximum direction error - the semi-major axis of a confidence error ellipsoid

\[
\begin{align*}
HPL_{x,i} &= K_{\alpha_H} \sigma_{dH_{\text{max},i}} + K_{md_{\text{max},i}} \sigma_{H_{\text{max},i}} \\
HPL_{i} &= K_{\alpha_H} \sqrt{\sigma_{dE,i}^2 + \sigma_{dN,i}^2} + K_{md,i} \sqrt{\sigma_{E,i}^2 + \sigma_{N,i}^2} \\
VPL_{i} &= K_{\alpha_V} \sigma_{dV,i} + K_{md,i} \sigma_{V,i}
\end{align*}
\]

\[
\beta = \frac{P(I)_H}{\{P(|dx_H|_o \geq HPL_o \mid CF) \times PCF + P(|dx_H|_o \geq HPL_o \mid IF) \times PIF + \sum_{i=1}^{m} P(|dx_H|_i \geq HPL_i \mid IF) \times PIF\}}
\]

\[
K_{\alpha_H,i} = -Q^{-1}\left(\frac{\alpha}{2m}\right), \quad K_{md,i} = -Q^{-1}(\beta)
\]

\[
K_{\alpha_H} = \sqrt{-2 \times \ln(\alpha)}, \quad K_{md_{\text{max},i}} = \sqrt{-2 \times \ln(\beta)}
\]
Doppler-based and IMU/SS Protection Levels

\[ HPL_{\zeta,i} = K_{md_{max,i}} \sigma_{H_{max,i}} + \cos (\theta - \zeta) B_i \]

\[ HPL_i = K_{md,i} \sqrt{\sigma_{E,i}^2 + \sigma_{N,i}^2} + B_i \]

Bias for Doppler

\[ B_i = \sqrt{(a_1^T S \begin{bmatrix} b_{vE} \\ b_{vN} \end{bmatrix})^2 + (a_2^T S \begin{bmatrix} b_{vE} \\ b_{vN} \end{bmatrix})^2} \]

Bias for IMU/SS

\[ B_i = \sqrt{(a_1^T S \begin{bmatrix} b_{\theta_{IMU}} \\ b_v \end{bmatrix})^2 + (a_2^T S \begin{bmatrix} b_{\theta_{IMU}} \\ b_v \end{bmatrix})^2} \]
Measuring changes in position affects HPL

\[
\begin{bmatrix}
E_i \\
N_i
\end{bmatrix} = \frac{\Delta t}{2} \begin{bmatrix}
1 & 0 & 1 & 0 \\
0 & 1 & 0 & 1
\end{bmatrix} \begin{bmatrix}
\nu_{E_{i-1}} \\
\nu_{N_{i-1}} \\
\nu_{E_{i}} \\
\nu_{N_{i}}
\end{bmatrix} + \begin{bmatrix}
E_{i-1} \\
N_{i-1}
\end{bmatrix}
\]

- For Doppler-based and IMU/speedometer positioning: The covariance matrix increases with time until updates are provided.

\[
Q_{EN_i} = A \ Q_{obs} \ A^T + Q_{EN_{i-1}}
\]

Accuracy requirement

Accuracy (95%) = \( K_{acc} \ \sigma_H < \text{threshold} \), where \( K_{acc} = 1.96 \).
Testing

- kinematic test in Tokyo
- Trimble RTK (10Hz)
- GPS, GLONASS and BeiDou
- a Bosch-consumer grade MEMS IMU
  The heading error of this IMU ranged from -2° to 5°, can accumulate to 10° after 30 min if left uncalibrated.
- Speed sensor (SS): $\sigma = 5$ cm/s
- GNSS-Doppler: $\sigma = 10$ cm/s.
- Reference: PPK & POS/LV
RTK Results

- Use different constellations

\[ \beta = 1 \times 10^{-4} \]
## RTK Results

Median **HPL** - different integrity risk probabilities (m)

<table>
<thead>
<tr>
<th>β</th>
<th>$1 \times 10^{-2}$</th>
<th>$1 \times 10^{-3}$</th>
<th>$1 \times 10^{-4}$</th>
<th>$1 \times 10^{-5}$</th>
<th>$1 \times 10^{-6}$</th>
<th>$1 \times 10^{-7}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>G+R+B</td>
<td>0.102</td>
<td>0.136</td>
<td>0.164</td>
<td>0.188</td>
<td>0.210</td>
<td>0.228</td>
</tr>
<tr>
<td>G+R</td>
<td>0.116</td>
<td>0.146</td>
<td>0.186</td>
<td>0.212</td>
<td>0.236</td>
<td>0.258</td>
</tr>
<tr>
<td>G+B</td>
<td>0.108</td>
<td>0.144</td>
<td>0.172</td>
<td>0.198</td>
<td>0.220</td>
<td>0.240</td>
</tr>
<tr>
<td>G</td>
<td>0.132</td>
<td>0.172</td>
<td>0.208</td>
<td>0.232</td>
<td>0.264</td>
<td>0.290</td>
</tr>
</tbody>
</table>

Median **HPL_{md}** (m)

<table>
<thead>
<tr>
<th>β</th>
<th>$1 \times 10^{-2}$</th>
<th>$1 \times 10^{-3}$</th>
<th>$1 \times 10^{-4}$</th>
<th>$1 \times 10^{-5}$</th>
<th>$1 \times 10^{-6}$</th>
<th>$1 \times 10^{-7}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>G+R+B</td>
<td>0.086</td>
<td>0.106</td>
<td>0.122</td>
<td>0.138</td>
<td>0.150</td>
<td>0.162</td>
</tr>
<tr>
<td>G+R</td>
<td>0.134</td>
<td>0.164</td>
<td>0.190</td>
<td>0.212</td>
<td>0.232</td>
<td>0.250</td>
</tr>
<tr>
<td>G+B</td>
<td>0.128</td>
<td>0.158</td>
<td>0.182</td>
<td>0.204</td>
<td>0.222</td>
<td>0.242</td>
</tr>
<tr>
<td>G</td>
<td>0.148</td>
<td>0.182</td>
<td>0.210</td>
<td>0.234</td>
<td>0.258</td>
<td>0.276</td>
</tr>
</tbody>
</table>

More const. ☞ more sats and better geometry ☞ better integrity monitoring

Less β ☞ larger HPL ☞ lower availability of integrity monitoring.
RTK Results

- The model can be initially validated.
- A few cases where the ambiguity were missed by one or two cycles. The HPL adapt and bound this error.
- With correct ambiguity fixing, HAL < 0.5 m.
- RAIM availability > 99% even when using $\beta$ of $1 \times 10^{-7}$.
- HPLs bounding the HPE at the design integrity risk.
Doppler-based Positioning

- Doppler observations for an extended period of time.
- Reinitialized every 1 min.
- HPL Sawtooth trend: error grow-calibration.
- HPE was bounded by the HPL.

\[
\beta = 1 \times 10^{-4}
\]
Impact of the allowed probability of integrity risk

HPL doubled when integrity risk increased from $1 \times 10^{-2}$ to $1 \times 10^{-7}$
Results of IMU/Speedometer

- The growing heading bias in-between IMU calibrations was the major source that affected the HPL.
- Error > 1.5 m in less than 20 sec after calibration.
- Limited to non-precision car manoeuvring or use a better grade IMU.
Integrated Systems

- Positioning availability: RTK (72.2%), Doppler-based (25.8%), IMU/SS (2%).
- An overall integrity monitoring availability more than 99% (HPE<HPL<HAL).
- These accuracy capabilities have to be taken into consideration when assigning tasks in ITS.

$$\beta = 1 \times 10^{-4}$$
Conclusions

- Positioning continuity for C-ITS is proposed using GNSS RTK integrated with low-cost MEMS IMU and automotive sensors.
- To ensure trustworthy positioning New IM models are proposed.
- The use of more constellations, while improves availability of RTK helps in reducing the HPL; and thus, improves availability of IM.
- HAL of 0.5 m can be selected for RTK with
  - RAIM availability > 99% .
- Doppler-based or IMU/SS provides positioning can bridge RTK in critical situations, however, they have less integrity & accuracy.
Thank you …

Reflection and Questions