A Train Integrity Solution based on GNSS Double-Difference Approach

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Roadmap

• Introduction to ERTMS/ETCS

• Train integrity issue

• Proposed solution

• Protection Level evaluation

• Simulation results

• Conclusions
ERTMS / ETCS (European Railway Traffic Management System / European Train Control System) is the standard for European railways. There are three levels:

- **Level 1**: Train must be able to evaluate its own position and to determine whether no carriage has been decoupled.
- **Level 2**: Movement authorities
- **Level 3**: Virtual Track Circuit
Train Integrity

**Issue:**
With the term train integrity we mean the ability to determine whether all the carriages are still coupled each others.

**Goal:**
Define a Virtual Track Circuit to reduce operational cost and increase the line capacity.

**Solution:**
Use a double difference approach between a couple of GNSS receiver located respectively at the head and at the end of the train. In such a way it is possible to estimate the train length with a little time delay.
Why satellite technology?

Main advantages are:

• Reduction of operational and maintenance cost
• Increasing of line capacity

Market perspective:

• Cost-effective solution to increase safety on low traffic lines
• Increase traffic on high-speed lines

Main challenge:

• Fulfill the SIL-4 requirements in terms of THR (Tolerable Hazard Rate) imposed for railways \((i.e. \, THR \leq 10^{-9}/h)\)
Reference architecture

SPACE SEGMENT

EGNOS

EDAS

Radio Block Center (RBC)

TALS

LDS & Train Integrity

Track Area Augmentation Network

RS 1

RS 2

... RS n
Double Difference approach

\[ SD_i = \| X_i^{Sat} \left[ T_i^{Sat} (k) \right] - X^{Track} \left[ s_H \left( T_i^{Rx_H} (k) \right) \right] - X_i^{Sat} \left[ T_i^{Sat} (k) \right] - X^{Track} \left[ s_E \left( T_i^{Rx_E} (k) \right) \right] = r_i^{Rx_H} \left[ 1 - \langle \hat{e}^{i}_{Rx_H}, \hat{e}^{i}_{Rx_E} \rangle \right] - \langle b, \hat{e}^{i}_{Rx_E} \rangle, \]

\[ DD_{Rx_HRx_E}^{ij} = SD_i - SD_j = r_i^{Rx_H} \left[ 1 - \langle \hat{e}^{i}_{Rx_H}, \hat{e}^{i}_{Rx_E} \rangle \right] - \langle b, \hat{e}^{i}_{Rx_E} \rangle - r_j^{Rx_H} \left[ 1 - \langle \hat{e}^{j}_{Rx_H}, \hat{e}^{j}_{Rx_E} \rangle \right] - \langle b, \hat{e}^{j}_{Rx_E} \rangle = r_i^{Rx_H} \left[ 1 - \langle \hat{e}^{i}_{Rx_H}, \hat{e}^{i}_{Rx_E} \rangle \right] - r_i^{Rx_H} \left[ 1 - \langle \hat{e}^{i}_{Rx_H}, \hat{e}^{i}_{Rx_E} \rangle \right] + \langle b, \hat{e}^{i}_{Rx_E} - \hat{e}^{j}_{Rx_E} \rangle. \]

Mitigation of most of the iono, tropo and clocks errors
We adopt a constrained positioning algorithm to map the 3-D estimation problem into a 1-D estimation problem.

\[
G^{(m)} = \begin{bmatrix} \hat{e}_{bH}^{(m)} & \hat{e}_{bE}^{(m)} \end{bmatrix},
\]

\[
\begin{align*}
\hat{e}_{bH}^{(m)} &= \left[ \frac{\partial \mathbf{X}^{R_{XH}}}{\partial s} \right]_{s=S_{H}^{(m)}(k)} \\
\hat{e}_{bE}^{(m)} &= \left[ \frac{\partial \mathbf{X}^{R_{XE}}}{\partial s} \right]_{s=S_{E}^{(m)}(k)}
\end{align*}
\]

\[
H_{\text{constr}}^{(m)} = H^{(m)} g G^{(m)}
\]
We can define protection as a statistical over bound of the gap estimation error. In fact

\[
\hat{L} > \eta > \hat{L}
\]

decoupled

\[
\beta_p
\]

coupled

We have to link the train integrity issue with the satellite integrity issue.
Performance Assessment

\[ P_{Le} \approx \sqrt{2 \frac{b}{B}} \sigma_{dd_{Max}} \gamma_{Max} \sqrt{\lambda_{Max}} + k_e \sigma_{\varepsilon_L} \]

\[ k_e = \sqrt{2} \text{erfc}^{-1} \left( \frac{R_{\text{TrainIntegrity}}^{TH_e}}{N_{Dec} D_{\chi_{N_{RIM}}^{-1}}^{nc} \left[ D_{\chi_{N_{RIM}}^{-1}}^{-1} \left( 1 - P_{fe} \right), \lambda_{Max} \right] P_{SF}} \right) \]
Protection Level for single fault

To have a numerical reference of the protection level let us consider:

\[
\sigma_{dd_{Max}} = 2 \\
|g|_{Max} \leq 1 \\
B = 50 \text{ km} \\
b = 2.5 \text{ km}
\]

\[
SLOPE = 0.14 \quad \rightarrow \quad PL \square 7m
\]

In such a way it is possible to derive the Virtual Circuit Length considering the dynamical model of the train (dynamic coupling junctions).
Simulation results

Results are provided for both a typical passenger train (500 m length travelling at 108 km/h) and a heavy freight one (2500 m length with cruise speed of about 80 km/h)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train weight</td>
<td>$1.275 \times 10^3$ kg</td>
</tr>
<tr>
<td>Carriage weight</td>
<td>35 t</td>
</tr>
<tr>
<td>Locomotive weight</td>
<td>120 t</td>
</tr>
<tr>
<td>$f_R$</td>
<td>0.02</td>
</tr>
<tr>
<td>$F_R$</td>
<td>$2.49 \times 10^4$ N</td>
</tr>
<tr>
<td>Receiver noise model</td>
<td>$\mathcal{N}(0.1,0.8)$</td>
</tr>
</tbody>
</table>
Train Length estimation error

Scenario with all coupled carriages

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We considered the following scenario:

- The train moves at constant speed
- The train is a rigid block (no dynamic coupling between carriages)
- One of the carriages decouples from the previous one
- The front train section continues its movement after the decoupling as if nothing has been occurred
- The tail section stops only by action of rolling resistance
- Track slope effect has been neglected
Train Length estimation error

Scenario with one decoupled carriage

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Dynamic effect mitigation

Train length L=2500 m

We use a median filter with window size equal to 10 epochs. In this way we reduce the outlier number in the error distribution by increasing the time to alert.
Conclusions

• Train Integrity function is key for the introduction of the ERTMS L3 system with GNSS technology

• We focused on the Virtual Track Circuit definition to estimate at the same time the train position and its length by the:
  – computation of Protection Level to evaluate the gap that can be protected by Virtual Track Circuit
  – verification that the theoretical model fulfils the SIL-4 (Safety Integrity Level 4) requirements

• Computer-based simulations have demonstrated the performance in terms of estimation error with different train lengths:
  – 250 m
  – 2500 m

• A median filter approach has been introduced to minimize the outlier number in the distribution by increasing the time to alert
Thank You for your kind attention