GNSS-based Positioning Scheme & Application in Safety-critical Systems of Rail Transport
1. Introduction
2. Challenges
3. Solutions
Introduction

How Modern Railway Signal Works?
Signalling System: Track Circuit
History of Signalling Systems

Diversity of European ATP systems

ETRMS/ETCS Cockpit
Introduction

Train Control Systems: Positioning Scheme

A token being offered by a signalman on the Keighley and Worth Valley Railway (from Wikipedia)
Train Control Systems: Positioning Scheme

ETCS System Components

- EVC
- GSM-R Network
- DMI
- RBC
- Wheel Sensor
- Balise Reader
- Radar
- Balise

Accumulated error
Calibration

speed, location
speed, location
Train control systems: Balise

- 2.5 km
- More in station
- Expensive
- difficult to maintain

Introduction
Signalling System: Fixed Block & Moving Block

Mainstream Signalling System

Direction of Travel

Block A Block B Block C Block D Block E

Train 2 Signal Signal Signal Signal Signal Train 1

Signalling System in the Future

Direction of Travel

Normal Speed

Braking Curve for Train 3 Braking Curve for Train 2 Braking Curve for Train 1

Train 3 Train 2 Train 1

*THE DEVELOPMENT AND PRINCIPLES OF UK SIGNALLING
Next-Generation Train Control System

- No track circuit
- Ability to determine train integrity on board
- No or less balise
- Trains find their position themselves
- Full radio-based train spacing
- Moving Block
Introduction

- Location info.
- Time info.
- Short messages (BDS)

- with high accuracy
- in all weather conditions
- anywhere on or near the Earth
- Cost-efficient
- available 24/7/365
EC and European Railway Agency (ERA) launched many projects to promote the progress of GNSS-based railway applications.

GPS-based PTC (Positive Train Control) had been equipped in the US and China (Qinghai-Tibet Line).

ATLAS 400, an European GPS-based train control system

 GNSS is a worldwide, cost-efficient approach to locate the target, which makes GNSS-based positioning become one of the most promising positioning solutions for the next-generation train control system.
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GNSS was refused by railway:

- ETCS (European Train Control System) and CTCS (Chinese Train Control System) have been standardized in the last two decades.
- Balise and STM (Specific Transmission Module) are necessary in ETCS-1,2.
Challenges

- GNSS was refused by railway:

  - Accuracy of distances measured on-board:
    \[ \pm (5m + 5\% S) \]
  - Accuracy of distinguishing parallel tracks: 1.5m
GNSS was refused by railway: There is a wall!!

- Railway applications must meet the requirements for Reliability, Availability, Maintainability, and Safety
- GNSS performance parameters, which are derived from aviation, are SIS Availability, Integrity, Continuity
- Safety: According to CCS TSI 2012/88/EU, for the hazard ‘exceeding speed and/or distance limits advised to ERTMS/ETCS’ the tolerable rate (THR) is $10^{-9}$/h for random failure, for on-board ERTMS/ETCS and for track-side, and positioning unit is just one of many subsystems.

1. Introduction

2. Challenges

3. Solutions
Solutions:

- Pseudorange-based GNSS
- Carrier-phase-based GNSS
- SPS
- DGNSS
- RTK
- PPP

Potentially:
- High Accuracy
- High Availability
- High Safety
Solutions: Why PPP?

**Differential solutions**

\[ \phi_i = \rho_i + \varepsilon_i \]

\[ -\phi_j = -\rho_j - \varepsilon \]

**PPP solutions**

\[ \phi_k = \rho_k + \varepsilon_k \]

- Station movements that result from geophysical phenomena such as tectonic plate motion, Earth tides and ocean loading enter the PPP solution in full, as do observation errors resulting from the troposphere and ionosphere.
- Relevant satellite specific errors are satellite clocks, satellite antenna phase center offset, group delay differential, relativity and satellite antenna phase wind-up error.
- Receiver specific errors are receiver antenna phase center offset and receiver antenna phase wind-up.

- In comparison with DGNSS, PPP has higher accuracy (centimetre to decimetre level*)
- Compared with RTK, PPP requires fewer reference stations globally distributed. PPP gives a highly redundant and robust position solution

* M.D. Laínez Samper et al, Multisystem real time precise-point-positioning, Coordinates, Volume VII, Issue 2, February 2011
Solutions: PPP-based multi-sensor fusion

IMU: Inertial Measurement Unit  ODO: odometer  EKF: Extended Kalman Filter
## Scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>GNSS/PPP</th>
<th>IMU</th>
<th>ODO</th>
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</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>available</td>
<td>not converged</td>
<td>available</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>available</td>
<td>converged</td>
<td>available</td>
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<tr>
<td>Scenario 3</td>
<td>unavailable</td>
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</table>
On-site test

Trajectory of On-site Test

Position Error

GNSS/INS Kalman Filter compares with GNSS position

- GNSS/INS Kalman Filter
- GNSS Position Info.
Simulation test

SPIRENT Simulator

Navigation Trajectory
Solutions: PPP-based multi-sensor fusion

*GNSS position error ~ N(0,1); GNSS velocity error ~ N(0,0.01); ODO velocity error ~ N(0,0.01)
Solutions: PPP-based multi-sensor fusion

*GNSS position error ~ N(0,1); GNSS velocity error ~ N(0,0.01); ODO velocity error ~ N(0,0.01)
Quality Control: Detection, Identification and Adaptation (DIA)

- Based on consistency check of innovations:
  \[ t_k = \frac{v_k^T Q^{-1}_{v_k} v_k}{m_k} \]
## Quality Control: Detection, Identification and Adaptation (DIA)

<table>
<thead>
<tr>
<th>Bias (unit: m/s)</th>
<th>Detected</th>
<th>Missed Detection</th>
<th>Success Rate</th>
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<tr>
<td>0</td>
<td>1000</td>
<td>20</td>
<td>98.04%</td>
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<tr>
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<td>1020</td>
<td>0</td>
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<table>
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</tr>
<tr>
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<td>98.04%</td>
</tr>
<tr>
<td>10</td>
<td>1020</td>
<td>0</td>
<td>100%</td>
</tr>
</tbody>
</table>
Threshold

\[ \text{THR} \leq 10^{-9}/h \]
Further Research

- DIA global test
- Track maps aided
- PPP integrity monitoring scheme
Thank You