Integrated Navigation Systems
- Fusing GNSS with Inertial Sensors -

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Overview

• Basics of Global Navigation Satellite Systems (GNSS)

• Basics of Inertial Navigation Systems (INS)

• GNSS/INS Data Fusion
  • Loosely Coupled GNSS/INS Integration
  • Tightly Coupled GNSS/INS Integration
  • Tightly Coupled GNSS/INS Smoother
  • Deeply Coupled GNSS/INS Integration
  • Platform Model Aided Navigation System
  • Inertial Aided GNSS Compass
Basics of Global Navigation Satellite Systems (GNSS)

Properties of single GNSS receiver:
- Position coordinates
- Velocity vector
- No attitude Information
- Dependant of at visibility of least 4 GNSS satellites

\[ c\Delta T_s = \sqrt{(X_s - X_u)^2 + (Y_s - Y_u)^2 + (Z_s - Z_u)^2} + c\delta t_u \]

Measured Time Delay
Satellite/Receiver-Coordinates
Receiver-Clock Error
Basics of Inertial Navigation Systems (INS)

Ringlaser Gyro (RLG)

Capacitive Accelerometer

Fiber Optic Gyro (FOG)

Vibrating Beam Accelerometer
Coordinate Systems

- **Inertial Frame**: reference to accelerometer and rotation rate measurements
- **Body Frame**: reference to mounting of accelerometers and gyroscopes
- **Navigation Frame**: north, east, down relative to earth surface
Inertial Measurement Unit (IMU)
- 3 orthogonal rotation sensors
- 3 orthogonal accelerometers

+ Strapdown Algorithm (SDA)
- Transformation of accelerometer data from body frame into navigation frame by gyroscope measurement data
- Integration of accelerometer data

= Inertial Navigation System (INS)
- position coordinates
- velocity vector
- attitude angles
INS Error Estimation

For a straight flight and for short time periods the accumulated position error is given by:

\[
\Delta s = \int_0^t \int_0^{t'} \Delta a_{ges}(t'') \, dt'' \, dt'
\]

\[
= \Delta s_0 \quad \text{(initial position error)}
\]

\[
+ (\Delta v_0) \, t \quad \text{(initial velocity error)}
\]

\[
+ \frac{1}{2} (\Delta a) \, t^2 \quad \text{(bias accelerometer)}
\]

\[
+ \frac{1}{6} g (\Delta \omega) \, t^3 \quad \text{(bias gyroscope)}
\]

\[
+ \frac{1}{2} g (\Delta \Phi) \, t^2 \quad \text{(initial alignment error)}
\]

\[
\text{time} = 6 \text{ minutes}
\]

\[
\Delta v_0 = 1 \text{ km/h} \rightarrow \Delta s = 100 \text{ m}
\]

\[
\Delta a = 1 \text{ mg} \rightarrow \Delta s = 650 \text{ m}
\]

\[
\Delta \omega = 1^\circ/\text{h} \rightarrow \Delta s = 380 \text{ m}
\]

\[
\Delta \Phi = 1 \text{ mrad} \rightarrow \Delta s = 650 \text{ m}
\]
**Inertial Navigation**
- Measurement of rotation rate and acceleration
- Calculation of position, velocity vector and attitude
- Inherently autonomous
- Updaterate typically 1 ms
- Short term stability

**GNSS**
- Measurement of pseudoranges and range rates to satellites
- Calculation of position and velocity vector
- Dependant from satellite signals
- Updaterate 0.1 - 1 s
- Long term stability

**Integration with Fusion Filter**
- Position, velocity and attitude
- Long term stability
- High update rate
Example: correction of strapdown result by position aiding

1-dim measurement of acceleration $a_m = a + \Delta a \rightarrow SDA \rightarrow$ estimated position $s + \Delta s$

Cause of position error: $\Delta s = \Delta s_0 + (\Delta v) t + \frac{1}{2} (\Delta a) t^2$

Correction of position, velocity and accelerometer bias, aided by GNSS position measurement:
- corrected position = weighted mean between estimation and measurement
- increase of estimated velocity
- increase of measured accelerometer data by adjustment of estimated accelerometer bias
Principle of Data Fusion by Kalman Filter

**Prädiktion:**

\[ \tilde{x}_{k+1}^- = \Phi_k \hat{x}_k^+ + B_k \tilde{u}_k \]
\[ P_{k+1}^- = \Phi_k P_k^+ \Phi_k^T + Q_k \]

**Estimation:**

\[ K = P_k^- H_k^T H_k P_k^- H_k^T + R_k \]
\[ \hat{x}_k^+ = \tilde{x}_k^- - K_k \tilde{H}_k \hat{x}_k^- - \tilde{y}_k \]
\[ P_k^+ = I - K_k \hat{H}_k P_k^- \]

\[ f_X(x) \]

\[ x_k^+ \]

\[ x_{k+1}^- \]

\[ x_{k+1}^+ \]

\[ t \]

\[ x \]

\[ f_X(x) \]

\[ x_k^- \]

\[ x_{k+1}^- \]

\[ x_{k+1}^+ \]

\[ y_m \]
Loosely - Coupled GPS/INS Integration

- IMU
- Strapdown Algorithm (SDA)
  - SDA Corrections (position, velocity Bias)
  - Kalman Filter
  - Position, Velocity, Attitude
- GNSS
  - measured position and velocity vector
  - estimated position and velocity vector

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Simulation: INS Position Error

Growth of Position Errors at GPS Loss

Tactical Grade IMU
Gyro: 1 °/h
Accelerometer: 1 mg
Tightly - Coupled GPS/INS Integration

IMU → Strapdown Algorithm (SDA) → SDA Corrections (position, velocity Bias) → Kalman Filter → Pseudorange Prediction → \[ \rho_{präd} = \vec{h}(\vec{x}_k) \] → Position Velocity Attitude

Difference of position estimation und calculated satellite position

\[ \sum \rho_{mess} \] → GNSS

Satellite Ephemerides
Simulation Loosely vs. Tightly Coupled GNSS/INS

Position Error (m)

Time (s)

- Tightly
- Loosely

3 Sat.  2 Sat.  1 Sat.
Test Drives

- Real sensor data provided by:
  - ITE
  - BMW Group Forschung und Technik

- Access to onboard sensors (BMW only)

- Independent GPS/INS high accuracy reference component (RT3000, ITE gin2)

- Location of drives:
  - Karlsruhe
  - Munich

C++

Navigation-Filter

Analysis
Experimental Results: Loosely vs. Tightly
Tightly Coupled GNSS/INS Smoother

Bridging of von GPS Loss by means of Fixed Interval Smoother

- Smoother processes measurement data forward and backward in time → optimal bridging of GPS Loss
- Tightly coupled processing of DGPS-pseudoranges and carrierphases
- Resolving of carrier phase ambiguities
Tightly Coupled Smoother

- Data can be processed forward and reverse
- Resolved ambiguities are logged and re-used
- At least two runs are required to resolve most of the ambiguities
- After each KF run a smoother run can be involved
Field Test

Equipment

- Ashtech Z-FX (rover)
- Trimble 4000 SSi (base)
- Litef uFors 6, Litef B290

Field test

- Lasts 1h 18min
- Urban areas, highways, hills, forests
- Max base line separation: approx. 12km
Results: Bridging Outages I

3 min GPS outage due to trees

Source: GoogleEarth
Results: Bridging Outages II

Bird's eye view: 3 min GPS outage

Source: Landesvermessungsamt Baden-Württemberg
Deeply Coupled GNSS/INS Integration
- Simultaneous Navigation and Tracking -

- Research Topic
- GNSS Receiver Design with Integrated Inertialsensors
  - Optimization of GNSS Signal Tracking

- Objectives
  - Robust navigation and robust signal tracking at high dynamics and low C/N0, e.g. during jamming
  - Consideration of characteristic properties of carrier frequency measurement
  - Reduction of computation load by low measurement update rates

Deeply Coupled GNSS/INS - Overview

- GNSS/INS Integration
  - Complete Navigation Solution
  - GNSS receiver is sensitive to signal losses, signal interferences (jamming) and trajectory dynamics

- Aiding of GNSS-Reception by IMU

- Increased Robustness
Deeply Coupled GNSS/INS Integration

Standard approach:
- Receiver tracks each satellite individually
- No further tracking if satellite signal is blocked

New: Aiding by IMU
- Receiver tracks satellite signals using navigation solution
- Stabilization concerning: Jamming, Acceleration, Signal loss
Advantages

- Aiding at low C/N by IMU
- Aiding at high trajectory dynamics
- No re-acquisition after loss of GNSS signal necessary
Hardware Test with Space Segment Simulator

- Realtime System Test
- Scenario-Simulation
  - GPS Signal at Antenna Input
  - Rotationrate & Acceleration
- Variation
  - Trajectory Dynamics
  - Signal Strenght
  - Antenna Pattern
- Reproducibility
  - GPS Receiving Conditions
  - IMU Errors

Simulated Trajectory

GPS Space Segment Simulator

IMU-Simulation (Data)

Navigation System
- GPS Hardware
- Realtime OS
- GPS Software
- GPS/INS Integration

Position Result  Log-Data

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Jamming-Resistance

Stabilizes signal reception during jamming.

Good Reception \rightarrow Jamming

\[ \Delta \text{Pos.} [\text{m}] \]
\[ \Delta \text{Vel.} [\text{m/s}] \]
\[ \Delta \text{Ang.} [\text{deg}] \]

\[ \text{Position ecef} \]

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Stability during dynamic flight

Stabilizes satellite reception during acceleration
Deeply Coupled GPS/INS Integration for Pedestrian Navigation

Deeply Coupled System with SDR-GPS-Receiver

- Functionality
  - Aiding of GPS signal tracking by means of coupling with torso step detection system

HF Front-End: SiGe4120L
Integration of “step-coupling” into signal tracking

- Step length and direction provided by torso subsystem
- GPS Integration by Stochastic Cloning Kalmanfilter
- Seamless navigation even when crossing through buildings
# Platform Model Aided Navigation

## Methods
- Development of innovative non-linear data fusion filters
- Aiding navigation by means of dynamic vehicle models
- Vehicle model based prefiltering of sensor data

## Goals
- Improvement of estimation accuracy for position and attitude in GPS flights
- Limited growth of estimation errors during GPS outages
- Application to fixed wing aircrafts and rotorcrafts

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Mutual aiding of INS/VDM

- Model aided navigation can bound velocity errors
- Estimation of IMU biases and model parameters/wind

Model aided navigation could reduce error growth significantly
Navigation filter structure

**Aims**
- Mutual aiding of INS and VDM
- Support of aiding sensors for VDM
The mechanical dynamic model of the vehicle estimates the movements of the body according to the control inputs for the fins or the motors. These estimated body motions are fused with the estimated motions of the INS within a central Kalman filter.
Simulation Result for a Quadrocopter with MEMS Inertial Sensors

GNSS denied after 60 s
Inertial aided GNSS Compass

Attitude Determination System

- accurate **heading** and **elevation** information
- permanent **availability**
- high **integrity**

Inertial Attitude Determination

- continuous availability of attitude solution
- poorly observable yaw angles for low dynamics

GNSS Attitude Determination

- attitude solution without offset
- GNSS dropouts
- time consuming ambiguity resolution

Fusion of both systems to create a multi-sensor attitude determination system
extraction of attitude angles from estimated base vector:

\[ \psi = \arctan \left( \frac{\vec{r}_{AB, \text{east}}}{\vec{r}_{AB, \text{north}}} \right) \]

\[ \theta = \arcsin \left( \frac{\vec{r}_{AB, \text{down}}}{\left\| \vec{r}_{AB} \right\|} \right) \]

- processing of carrier phase measurement
- ambiguity resolution uses double differenced GNSS signals:

\[ \phi_{ij,AB} = \frac{1}{\lambda} \ e_i^T - e_j^T \cdot \vec{r}_{AB} + N_{ij,AB} \]
• propagation of attitude angles in a strapdown algorithm

• estimation of angle errors and gyroscope biases in an error state Kalman Filter

• Kalman Filter aiding:
  • accelerometer measurements for roll and pitch angles
  • magnetometer measurements for yaw angles
Multi-sensor attitude determination system

Pre-processing

carrier phase

double differenced carrier phase

BaseVec-Filter

Extended KF

arctan()

Base vector

integer ambiguities

floating ambiguities, covariances

yaw and pitch angle

acceleration, angular rate

yaw and pitch angle

sensor biases

attitude error

baseline length

Inertial attitude System

IMU

GPS Rec1

GPS Rec2

MAG

carrier phase

double differenced carrier phase

Extended LAMBDA

GNSS attitude system

Error-State Kalman Filter

GNSS attitude system

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Test Equipment

- **GNSS System:**
  - single-frequency *Magellan AC12* GNSS receivers
  - single-frequency *u-blox ANN-MS-1-00* patch antennas
  - baseline length: 20 cm

- **Inertial Attitude System**
  - *ADIS 16255* gyroscopes
  - *SCA 3000 D01* accelerometers
  - *HMC 5843* 3-axes magnetic field sensor
Time to First Fix

<table>
<thead>
<tr>
<th>Constraints</th>
<th>Mean TTFF</th>
<th># Fixes</th>
<th># wrong fixes</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>229 s</td>
<td>700</td>
<td>432</td>
</tr>
<tr>
<td>(\pm \Delta l = 5\text{cm})</td>
<td>48.1 s</td>
<td>900</td>
<td>3</td>
</tr>
<tr>
<td>(\pm \Delta \theta = 15^\circ)</td>
<td>1.4 s</td>
<td>900</td>
<td>0</td>
</tr>
<tr>
<td>(\pm \Delta \psi = 30^\circ)</td>
<td>1.02 s</td>
<td>900</td>
<td>0</td>
</tr>
</tbody>
</table>

**Graphs:**
- No constraints
- Base length constraints
- Base length and pitch constraints
- Base length, pitch and yaw constraints
Performance

<table>
<thead>
<tr>
<th>GNSS Solution</th>
<th>Mean</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yaw</td>
<td>6.5°</td>
<td>1.02°</td>
</tr>
<tr>
<td>Pitch</td>
<td>-0.05</td>
<td>3.6°</td>
</tr>
<tr>
<td>Baseline length</td>
<td>19.46 cm</td>
<td>1.55 cm</td>
</tr>
</tbody>
</table>

Highly accurate yaw angle estimation
Thank you for your attention!