On trajectory determination for photogrammetry & remote sensing: sensors, models & exploitation

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AGENDA

1. motivation and introduction
2. motion sensing & timing
3. trajectory error modelling and estimation
4. trajectory exploitation
5. conclusions

… a quick survey on trajectory determination for P&RS
INTRODUCTION

1. trajectory (function of time)
   \[ \{ n(t_0), \ldots, n(t_e) \}, \ n(t) \in N \]

2. navigation space, examples:
   \[ N = \mathbb{R}^3 \times \mathbb{R}^3 \times SO(3) \]
   \[ N = \mathbb{R}^3 \times \mathbb{R}^3 \times SO(3) \times \mathbb{R}^m \]
   \[ N = \mathbb{R}^3 \]

2. orientation / navigation (broad sense of orientation functions)

   navigation is real-time orientation
MOTION SENSING & TIMING
MOTION SENSING & TIMING

1. GNSS infrastructure

2. Inertial sensing & navigation

3. Timing
QUESTION: WHAT IS THIS?
SHORT ANSWER:

the Galileo 2 cm pseudorange E5 AltBOC revolution !!!

• precise, **accurate** and **robust code** positioning
• **single-frequency** ionospheric determination
ANSWER: Galileo E5 AltBOC (10,15)

**Tracking Accuracy and Ranging Precision**

<table>
<thead>
<tr>
<th>Signal Type</th>
<th>Open Sky</th>
<th>Multipath-Fading</th>
</tr>
</thead>
<tbody>
<tr>
<td>E5 AltBOC (15,10)</td>
<td>0.02 m (44 dB-Hz)</td>
<td>0.08 m (40 dB-Hz)</td>
</tr>
<tr>
<td>E1 CBOC (6,1,1/11)</td>
<td>0.25 m (40 dB-Hz)</td>
<td>2.00 m (36 dB-Hz)</td>
</tr>
</tbody>
</table>
ANSWER: Galileo E5 AltBOC (...) & E1 CBOC (...)

<table>
<thead>
<tr>
<th>RMSE (m)</th>
<th>K</th>
<th>S-1</th>
<th>S-5</th>
<th>S-10</th>
<th>S-30</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>μH</td>
<td>μV</td>
<td>μH</td>
<td>μV</td>
<td>μH</td>
</tr>
<tr>
<td>OS</td>
<td>0.07</td>
<td>0.19</td>
<td>0.07</td>
<td>0.15</td>
<td>0.06</td>
</tr>
<tr>
<td>TC</td>
<td>0.14</td>
<td>0.35</td>
<td>0.13</td>
<td>0.32</td>
<td>0.10</td>
</tr>
</tbody>
</table>

ENCORE PROJECT RESULTS (FP7, GSA)

SINGLE-FREQUENCY IONO-DELAY ESTIMATION WITH Galileo E5 (& BeiDou B2) AltBOC

1991-old idea

group-delay and phase-delay have opposite signs

of limited practical interest with the original GPS signals

SX5 project (FP7, GSA): CAC/ANSA 1-2 cm (few min)

GNSS INFRASTRUCTURE BY 2020

• GPS (32), GLONASS (29), BeiDou (30+5) & Galileo (30)
• 30 - 40 satellites in-view at any time
• 12 signals
• ≈ 1000 channel receivers

• IGS products (GPS)
  - orbits: 2.5 cm (1D, RMS)
  - clocks: 75 ps (RMS) – 75 x 10^{-12} s – 2.25 cm
QUESTION: WHAT IS THIS?

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>2.4 x 2.4 x 1 cm³</td>
</tr>
<tr>
<td>Weight</td>
<td>7 g</td>
</tr>
<tr>
<td>Power consumption</td>
<td>99 mW</td>
</tr>
<tr>
<td>In-run / run-to-run bias</td>
<td>3 / 1800 deg/h</td>
</tr>
<tr>
<td>In-run</td>
<td>&lt; 0.01 m/s²</td>
</tr>
<tr>
<td>Cost</td>
<td>2 k€</td>
</tr>
</tbody>
</table>
SHORT ANSWER

AV plots courtesy of CTTC.
PROPER ANSWER: THE EPSON M-G363/350 IMU

AV plots courtesy of CTTC.
SQUARE ROOT OF ALLAN VARIANCE

\[ \sigma(\tau) \]

- **Introduction**
- **Motion sensing & timing**
- **Modelling & estimation**
- **Exploitation**
- **Conclusions**

\[ q \quad T = 3^{1/2} \]
\[ s = -1 \]

\[ n \quad T = 1 \]
\[ S = -0.5 \]

\[ b \quad s = 0 \]

\[ r \quad T = 3 \]
\[ S = 0.5 \]

\[ d \quad T = 2^{1/2} \]
\[ s = 1 \]
NICE 2 km-COIL FOG @ 130 k€ / IMU

Allan Standard deviation of FJI-20090719 Gyros

AV plots courtesy of CTTC
## COMPARATIVE NOISE FIGURES FROM AV

<table>
<thead>
<tr>
<th>IMU</th>
<th>w (deg/h)</th>
<th>A (m/s²)</th>
<th>k€</th>
</tr>
</thead>
<tbody>
<tr>
<td>iMAR FJI</td>
<td>0.10</td>
<td>0.00001</td>
<td>130</td>
</tr>
<tr>
<td>Honeywell CIMU</td>
<td>1.00</td>
<td>0.00025</td>
<td>60</td>
</tr>
<tr>
<td>Honeywell HG1700</td>
<td>2.00</td>
<td>0.00025</td>
<td>20</td>
</tr>
<tr>
<td>NavChip</td>
<td>6.00</td>
<td>0.00050</td>
<td>2</td>
</tr>
<tr>
<td>EPSON M-G350</td>
<td>12.00</td>
<td>0.00060</td>
<td>2</td>
</tr>
<tr>
<td>Maxim MAX21100</td>
<td>36.00</td>
<td>0.00320</td>
<td>0.003</td>
</tr>
</tbody>
</table>

MEMS-MEMS / PP / P: 0.02-0.05 m  V: 0.01-0.02 m/s  A: 0.03-0.10 deg
**QUESTION:** WHAT IS THIS?

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>4 x 3.5 x 1.1 cm³</td>
</tr>
<tr>
<td>Weight</td>
<td>35 g</td>
</tr>
<tr>
<td>Power consumption</td>
<td>120 mW</td>
</tr>
<tr>
<td>Stability (Allan Variance)</td>
<td>$8 \times 10^{-12}$ (over 1000 s interval)</td>
</tr>
<tr>
<td>MTBF</td>
<td>&gt; 100000 h</td>
</tr>
<tr>
<td>Cost</td>
<td>2 k€</td>
</tr>
</tbody>
</table>
SHORT ANSWER:

the revolution of low-cost precision portable timekeeping!

• 1 µs over 24 h time interval
• GPS-timing equivalent over 1 h
ANSWER: A CHIP-SCALE ATOMIC CLOCK

- It can bridge GPS timing gaps for about 3000 s
  - guarantees multi-sensor synchronization (e.g., radar)
- It can detect jamming and spoofing
- It “reduces” the number of essential unknowns from 4 to 3
- In GNSS positioning: correlated height & time unknowns
  - improvement of up to 60% in the height component

ERROR MODELLING & ESTIMATION
ERROR MODELLING & ESTIMATION

1. trajectory-level error models
2. sensor-level error models
3. relative & absolute error models
4. navigation and geodetic approaches to estimation
TRAJECTORY-LEVEL ERROR MODELS

- model the results of the errors, not the sources
- in principle, less sound/effective than sensor-error models
- old, good friends of us (GPS-shifts of GPS AT)
- easy to implement in software
- recently being used in terrestrial mobile mapping systems
  step 2 of two-step INS/GNSS + inverse imaging
- most times deterministic
  - piecewise C^n polynomials, ...
SENSOR-LEVEL ERROR MODELS

- model the error sources
- in principle, the optimal strategy
- old stubborn friends (don't let themselves be modelled easily)
- usually being used in one-step INS/GNSS/… integration
  … but not in step 2 of two-step INS/GNSS + inverse imaging
- most times stochastic
  - random walk, 1st order Gauss-Markov
ABSOLUTE & RELATIVE ERROR MODELS

1. tPA absolute error models do not allow to approach the correlated nature of trajectory errors (and of outlier effects).

2. tPA relative error models closer reflect actual errors; e.g. a GPS cycle slip.

NAVIGATION “vs” GEODETIC ESTIMATION

INS/GNSS/… applications for trajectory estimation

- **navigation**: always a **real-time** task
  - estimation: predictive filtering (PF)
    sequential least-squares with SE and SDE
    or more sophisticated like UKF or PF

- **orientation**: usually a **post-mission** task
  - estimation: PF, **why? Is there any geodetic approach?**
    ... 2004-old idea of dynamic networks

  dynamic networks: approximate the derivatives of an SDE by finite differences.
NAVIGATION & GEODETIC ESTIMATION

Introduction

Motion sensing & timing

Modelling & estimation

Exploitation

Conclusions

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velocity improvement
cross-overs
dynamic networks
vs
KFS
TRAJECTORY EXPLOITATION
TRAJECTORY EXPLOITATION

1. the contents of INS/GNSS-derived trajectories

2. 4D spatiotemporal calibration

3. simplification of image matching (FAST AT)
CONTENTS OF INS/GNSS-TRAJECTORIES

- an image 12-orientation parameters \((P, V, A, \Omega)\)

\[
\begin{align*}
  s^l_c &= (p^l, v^l, \gamma^l, \omega^l_c) \\
  o^l_c &= (p^l, \gamma^l_c)
\end{align*}
\]

\[
p^l = v^l, \quad \dot{R}(\gamma)^l_c = R(\gamma)^l_c \Omega(\omega)^l_c.
\]

- \((P, V, A, \Omega)\) have a well-defined mathematical structure

- applications to 4D spacetime calibration, image deblurring or modelling of focal-plane shutter effects

4D SPACETIME SENSOR/SYSTEM CALIBRATION

1. positioning / timing use to be non-separable: e.g., GPS positioning
2. orientation / calibration not an exception; e.g., sync. errors
3. 1 ms time-error determination is achievable using

\[ s_c^l = (p^l, v^l, \gamma_c^l, \omega_{lc}^c) \]

and appropriate spacetime orientation-calibration models

AT WITH LESS IMAGE MATCHING

a quality trajectory can be used for

• direct sensor orientation (DiSO)

• integrated sensor orientation (ISO)

• also for bridging non-overlapping images or reduce image processing

FAST AT: MAXIMAL SIMPLIFICATION / BRIDGING

- Image and tPA Aerial Control
- Ground Control Point (GCP)

Fast AT block: $18 + 13 + 20 + 12$ images, photo-measurements in $2 + 3 + 3 + 2$ images, 2 sub-blocks, no need for image/stripe overlap, image overlap recommended in areas with GCPs.
SIMPLIFICATION OF IMAGE MATCHING

Pavia block

Fast AT
ISO
41
62
\( \mu_H \) (mm)
DiSO
125
35
\( \mu_V \) (mm)
DiSO
265

Fast AT
ISO
42
59
\( \mu_H \) (mm)
DiSO
125
36
\( \mu_V \) (mm)
DiSO
265

Vaihingen/Enz gsd7 block

Fast AT
ISO
31
28
\( \mu_H \) (mm)
DiSO
65
58
62
\( \mu_V \) (mm)
DiSO
191

Fast AT
ISO
26
30
\( \mu_H \) (mm)
DiSO
65
51
53
\( \mu_V \) (mm)
DiSO
191

Vaihingen/Enz gsd20 block

Fast AT
ISO
50
65
\( \mu_H \) (mm)
DiSO
133
98
112
\( \mu_V \) (mm)
DiSO
387

Fast AT
ISO
48
62
\( \mu_H \) (mm)
DiSO
133
96
106
\( \mu_V \) (mm)
DiSO
387
CONCLUSIONS

1. on-going progress in motion sensing with cost reduction
   - GNSS infrastructure
   - inertial sensing
   - timing

2. on-going progress in trajectory determination
   (geomatic, navigation & robotics community)
   - trajectory-level error models
   - sensor-level error models

3. better ways of trajectory exploitation
DO NOT MISS THE
February 10-12, Lausanne, EPFL - www.eurocow.org