04: SENSOR SYNCHRONIZATION

MSC GEODETIC ENGINEERING

MSR-02: ADVANCED TECHNIQUES FOR MOBILE SENSING AND ROBOTICS (GEODESY TRACK)

04: SENSOR SYNCHRONIZATION

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ADVANCED TECHNIQUES FOR MOBILE SENSING AND ROBOTICS – LECTURE CONTENT

(1) Mobile Laser Scanning
(2) Trajectory Estimation
(3) System Calibration
(4) Sensor Synchronisation
(5) From Images to Point Clouds (SfM)
(6) Accuracy of Point Clouds I
(7) Accuracy of Point Clouds II
(8) Deformation Analysis with Point Clouds I
(9) Deformation Analysis with Point Clouds II
CHAPTER 1: 
MOBILE LASER SCANNING

\[ \mathbf{p}_{\text{object}}^{\text{global}}(t_s) = \mathbf{T}_{\text{global}}^{\text{body}}(t_s) \cdot \mathbf{T}_{\text{body}}^{\text{sensor}} \cdot \mathbf{p}_{\text{object}}^{\text{sensor}}(t_s) \]

- Review of involved coordinate systems /frames
- Derivation of detailed georeferencing equation for the example of mobile laser scanning

\[
\begin{bmatrix}
x_e \\
y_e \\
z_e
\end{bmatrix} =
\begin{bmatrix}
t_x \\
t_y \\
t_z
\end{bmatrix} + \mathbf{R}_n^e(L, B) \cdot \mathbf{R}_b^n(\phi, \theta, \psi) \cdot
\begin{bmatrix}
\Delta x \\
\Delta y \\
\Delta z
\end{bmatrix} + \mathbf{R}_s^b(\alpha, \beta, \gamma) \cdot
\begin{bmatrix}
0 \\
d \cdot \sin b \\
d \cdot \cos b
\end{bmatrix}
\]
CHAPTER 2: TRAJECTORY PARAMETERS

\[
\begin{bmatrix}
  x_e \\
  y_e \\
  z_e
\end{bmatrix} = \begin{bmatrix}
  t_x \\
  t_y \\
  t_z
\end{bmatrix} + \mathbf{R}_n^e (L, B) \mathbf{R}_b^n (\phi, \theta, \psi) \cdot \begin{bmatrix}
  \Delta x \\
  \Delta y \\
  \Delta z
\end{bmatrix} + \mathbf{R}_s^b (\alpha, \beta, \gamma) \cdot \begin{bmatrix}
  0 \\
  d \cdot \sin b \\
  d \cdot \cos b
\end{bmatrix}
\]

- Review of inertial navigation, strapdown integration and Kalman Filtering
- Introduced Kalman Smoothing
- Evaluation of trajectory estimation
CHAPTER 3: SYSTEM CALIBRATION

\[
\begin{bmatrix}
  x_e \\
  y_e \\
  z_e
\end{bmatrix} = 
\begin{bmatrix}
  t_x \\
  t_y \\
  t_z
\end{bmatrix} + \mathbf{R}_{c}^{e}(L, B) \mathbf{R}_{n}^{b}(\phi, \theta, \psi) \cdot 
\begin{bmatrix}
  \Delta x \\
  \Delta y \\
  \Delta z
\end{bmatrix} + \mathbf{R}_{s}^{b}(\alpha, \beta, \gamma) \cdot 
\begin{bmatrix}
  0 \\
  d \cdot \sin b \\
  d \cdot \cos b
\end{bmatrix}
\]


- Overview of **system calibration** methods
- Detailed derivation of **plane based calibration**
CHAPTER 4: SENSOR SYNCHRONISATION

\[
\begin{bmatrix}
    x_e \\
    y_e \\
    z_e
\end{bmatrix} =
\begin{bmatrix}
    t_x \\
    t_y \\
    t_z
\end{bmatrix} +
R_c^e(L, B) R_n^b(\phi, \theta, \psi) \cdot 
\begin{bmatrix}
    \Delta x \\
    \Delta y \\
    \Delta z
\end{bmatrix} +
R_s^b(\alpha, \beta, \gamma) \cdot 
\begin{bmatrix}
    0 \\
    d \cdot \sin b \\
    d \cdot \cos b
\end{bmatrix}
\]

• Why is sensor synchronization important?
• Methods for sensor synchronization
# Typical Data Rates

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Typical rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>GNSS receiver</td>
<td>1-10Hz</td>
</tr>
<tr>
<td>Inertial measurement Unit</td>
<td>100-1000Hz</td>
</tr>
<tr>
<td>Laser scanner</td>
<td>100-1000kHz (point rate), 10-100Hz (profile rate)</td>
</tr>
<tr>
<td>Camera</td>
<td>1-100Hz</td>
</tr>
<tr>
<td>Depth Cameras</td>
<td>1-100Hz</td>
</tr>
</tbody>
</table>
SENSOR SYNCHRONIZATION – WHY?

\[
\begin{bmatrix}
  x_e \\
  y_e \\
  z_e
\end{bmatrix}
= \begin{bmatrix}
  t_x \\
  t_y \\
  t_z
\end{bmatrix}
+ R^n_r(L,B) R^n_n(\phi, \theta, \psi) \cdot \begin{bmatrix}
  \Delta x \\
  \Delta y \\
  \Delta z
\end{bmatrix}
+ R^b_s(\alpha, \beta, \gamma) \cdot \begin{bmatrix}
  0 \\
  d \cdot \sin b \\
  d \cdot \cos b
\end{bmatrix}
\]

- Time difference \( dt=dt'-dt'' \) between scanner observation and trajectory parameter leads to wrong assignment of observations to the trajectory and therefore to a wrong transformation in the georeferencing equation.
- Error depends on moving speed and rotation rate.
SENSOR SYNCHRONIZATION – WHY?

TRANSLATION ERROR DUE TO TIME SYNC ERROR

---

The diagram illustrates the relationship between time sync error and translation error. The x-axis represents the time sync error (Δ T in milliseconds), and the y-axis represents the translation error (Δ x in centimeters). The graph shows that for a time sync error of 1 millisecond, the translation error is approximately 1 centimeter. For a walking speed of 1 meter per second, the translation error is minimal, while for a car in an urban area with a speed of 50 kilometers per hour, the translation error is significantly greater, indicating the importance of accurate sensor synchronization.
### SENSOR SYNCHRONIZATION – WHY?

#### REQUIRED TIME RESOLUTION [MILLISECONDS]

<table>
<thead>
<tr>
<th>Velocity</th>
<th>km/h</th>
<th>m/s</th>
<th>Spatial Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1 mm</td>
</tr>
<tr>
<td>3,6</td>
<td>1,0</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>10,8</td>
<td>3,0</td>
<td></td>
<td>0,3</td>
</tr>
<tr>
<td>100,0</td>
<td>27,8</td>
<td></td>
<td>0,04</td>
</tr>
<tr>
<td>200,0</td>
<td>55,5</td>
<td></td>
<td>0,02</td>
</tr>
</tbody>
</table>
SENSOR SYNCHRONIZATION – WHY?

ROTATION ERROR ➔ SCAN POINT ERROR DUE TO TIME SYNC ERROR

• Assume a 90° turn in 1 seconds
• rotation rate 90 °/sec
• $dt = 1\text{msec}$ leads to 0.1° angle error
• Assume 10m distance from the object to the scanner
• 0.1° Angle error lead to 1.5cm position error
SENSOR SYNCHRONIZATION – WHY?

MANIPULATING THE ENVIRONMENT, CONTROL AND ACTION

- Performing an action at a specific position also needs high synchronization accuracy, depending on movement speed.

Example: GNSS controlled sugar beet seeding.
SYNCHRONIZATION PROBLEMS

**Problem 1**) How to assign a time stamp to a measurement?

**Problem 2**) What clock to use for time stamping?

**Problem 3**) How to synchronize multiple clocks
SYNCHRONIZATION PROBLEMS

PC
Laptop
Raspberry PI
µController

Problem 1
Problem 1
Problem 1
Problem 1
Problem 1
SYNCHRONIZATION PROBLEMS
PROBLEM 1

HOW TO ASSIGN A TIME STAMP TO A MEASUREMENT?

• **Option 1:** The sensor already provides you with properly time tagged measurements ➔ go directly to Problem 2 (what is the time base?)

• **Option 2:** The sensor provides an electronic signal (e.g. pulse) at the moment when the measurement happens

• **Option 3:** The sensors perform the measurement at the moment it receives a trigger in form of an electronic signal (e.g. pulse)
PROBLEM 1 – OPTION 1 (STAMPED DATA)

GNSS RECEIVERS

• GNSS receivers always provide data which are properly time stamped in *Coordinated Universal Time (UTC)* (more on that later)

• Most Inertial measurement systems, which contain a GNSS receiver, also provide data (position, orientation, acceleration, velocity, angular rate) time stamped in UTC
GNSS RECEIVERS

- Higher grade GNSS receivers provide an electronic signal (PPS: Pulse Per Second) at the time a GNSS measurement is performed.
- This PPS can be also used to synchronize other clocks.

(More on that later)
INDUSTRY CAMERAS

- Industry cameras usually provide a trigger output synchronized with the shutter
CONSUMER CAMERAS

• With some camera the hot shoe (flash synchronization) can be used to generate an electronic signal
• Not possible with all cameras
• Sometimes restricts exposure time
LASER SCANNERS

- Most scanners provide a signal when the profile crosses 0°
PROBLEM 1: OPTION 3 (SEND TRIGGER)

LASER SCANNERS

• Some scanner mirror rotations can be synchronized with an external oscillation

• Does not really help with time synchronization, because it synchronizes oscillations not single events
PROBLEM 1: OPTION 3 (SEND TRIGGER)

CAMERAS

• Industry Cameras usually provide a trigger input signal

• Some consumer cameras also provide similar options

• Problem: It is not always clear, what happens between the trigger signal and the actual moment of exposure (e.g. autofocus, brightness adjustments, various settings)
**PROBLEM 1 – NO OPTION**

**USB CONNECTED DEVICES**

- USB connected sensors without any extra sync possibilities are in general problematic


Latency and jitter of button clicks in USB mice
PROBLEM 2

WHAT CLOCK TO USE FOR TIME STAMPING?

- Measuring time is based on the observation of a periodic process and counting the periods

<table>
<thead>
<tr>
<th>Periodic process</th>
<th>Representative time systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth rotation</td>
<td>Universal time (UT)</td>
</tr>
<tr>
<td></td>
<td>Greenwich sidereal time ($\Theta_0$)</td>
</tr>
<tr>
<td>Earth revolution</td>
<td>Terrestrial dynamic time (TDT)</td>
</tr>
<tr>
<td></td>
<td>Barycentric dynamic time (BDT)</td>
</tr>
<tr>
<td>Atomic oscillations</td>
<td>International atomic time (TAI)</td>
</tr>
<tr>
<td></td>
<td>Coordinated UT (UTC)</td>
</tr>
<tr>
<td></td>
<td>Reference time in satellite-based positioning systems</td>
</tr>
</tbody>
</table>
**TIME SYSTEMS**

- **Universal time (UT)** is based on the Earth Rotation. Different versions account for changing effects such as polar motion and changing rotation rates (e.g. UT1).

- **Atomic time (TAI)** is based on the duration of a state transition of the Cs$_{133}$ atom.

- **Coordinated UT (UTC)** is using atomic time seconds, but keeping a maximum distance of 0.9sec to UT1 (needs introduction of leap seconds).

- **Unix time** is the number of seconds since [UTC] 01.01.1970, ignoring leap seconds.

- **GPS time (GPST)** is maintained by the GPS monitoring network. GPST = UTC -18sec (leap seconds change when a UTC leap seconds change).
TIME SYSTEMS

LEAP SECONDS

[Graph showing leap seconds with UTC and UT1 markers and time intervals from 1.1.1972 to 1.1.2006.]
\[
\{\rho^{(k)}\}: \text{Pseudoranges (measurements)}
\]
\[
\{(x^{(k)}, y^{(k)}, z^{(k)})\}: \text{Satellite positions (known)}
\]
\[
\rho^{(k)} = \sqrt{(x^{(k)} - x)^2 + (y^{(k)} - y)^2 + (z^{(k)} - z)^2} - b
\]
\[k = 1, 2, ..., K\]

If \(K \geq 4\), solve for user position \((x, y, z)\),
and receiver clock bias \(b\)
GNSS

- If a GNSS receiver has a position fix, it also has a „time fix“
- The bias between the receiver clock and the GPS time standard is freshly estimated with about 10Hz
- A good receiver always updates its internal clock with the estimated offsets provides an electronic signal for every GPS time second (PPS)
- These information can be used to time stamp sensor data or synchronize other clocks.
- The PPS signal is stable within nanoseconds
Both receiver with fix

One receiver without fix (after 5min)

One receiver without fix (after 30min)
PROBLEM 3

HOW TO SYNCHRONIZE MULTIPLE CLOCKS?
PROBLEM 3 – CLOCK SYNC

OPTION 1: SYNC ALL CLOCKS WITH GNSS
PROBLEM 3 – CLOCK SYNC

OPTION 2: SYNCHRONIZE CLOCKS VIA CLOCK SYNC PROTOCOL
PRECISE TIME PROTOCOL (PTP)
PRECISE TIME PROTOCOL (PTP)

~ microseconds accuracy
NETWORK TIME PROTOCOL (NTP)

- A client measures round trip times to one or more servers of a higher hierarchy level (stratum)
- Based on different algorithms the offset is calculated
- Synchronization is accurate in the order of 10s of milliseconds
- Works well for server networks
- Control loops for time synchronization need some time to converge, not ideal for sensors
TIME SYNC EXAMPLE

IGG MOBILE MAPPING SYSTEM

Data file
timestamp (UTC) x y z
timestamp (UTC) x y z
timestamp (UTC) x y z
...

Interpolate

Data file
timestamp (UTC) acc_x acc_y acc_z ...
timestamp (UTC) acc_x acc_y acc_z ...
timestamp (UTC) acc_x acc_y acc_z ...
...

PPS

NMEA (GGA message contains UTC time)

~10^3 kHz

~1 kHz

Klingbeil: Advanced Techniques for Mobile Sensing and Robotics - Geodesy - 04 - Sensor Synchronization
TIME SYNC EXAMPLE: PRECISE SEEDING OF SUGARBEET

- RTK GPS
- Gyroscope
- Odometer
- Kalman Filter
- Realtime Processing

Controlled seeding wheel
TIME SYNC EXAMPLE: PRECISE SEEDING OF SUGARBEET

**Sensoren**
- Position
  - GPS Leica System1200
- Weg
  - Sick DFS60B CorreVit L400
- Drehrate
  - Bosch DRS-MM 1.0

**Steuerung**
- NMEA UTM
- Ethernet TCP
- PPS

**Bedienung**
- Laptop PC

**Aktuatoren**
- Säggregat mit angetriebenem Zellenrad des ILT- Uni Bonn
- Stift mit Antrieb Walter Pilot Signieranlage

**Klingbeil: Advanced Techniques for Mobile Sensing and Robotics - Geodesy - 04 - Sensor Synchronization**
TIME SYNC EXAMPLE: PRECISE SEEDING OF SUGARBEET

Aktuator Track

Deviations of measured plant positions from nominal position

Accuracy ~ 2 cm

WHAT YOU HAVE LEARNED TODAY

• Why is synchronization between sensors important?
• What synchronization accuracy is needed?
• What are the critical points in synchronization?
• How can GNSS receivers be used for synchronization?
• How can clocks in computer networks be synchronized?
• How is sensor synchronization realized in the IGG mobile mapping system?
THANKS