Real-Time fusion of sensors for navigation

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Outline

1. Introduction and motivation
2. Low-cost test platform (test trolley)
3. Integration extended Kalman Filter model
4. EKF filter input and reference data
5. Results
6. Conclusion
Introduction and motivation (1)

Autonomous lawnmower **with** border cable

[Image: Autonomous lawnmower with border cable]

https://powerequipment.honda.com/

Autonomous lawnmower **without** border cable

[Image: Autonomous lawnmower without border cable]

http://grauonline.de/cms2/?page_id=153
Introduction and motivation (2)

IMU

~10$

~550$

~10$

GNSS

~250$

Hi-end Mobile Mapping System

~50000$ - …
Low-cost test platform (test trolley) – v.1
The first EKF results using test platform version 1

EKF - RMS:
N = 0.25 m
E = 0.28 m
Sensors fusion and test data

<table>
<thead>
<tr>
<th>Drift (°/h)</th>
<th>IMU – fiber optic (0.1°/h)</th>
<th>Xsens - MEMS (10°/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N - RMS [m]</td>
<td>E - RMS [m]</td>
</tr>
<tr>
<td>0</td>
<td>0.029</td>
<td>0.042</td>
</tr>
<tr>
<td>10</td>
<td>0.029</td>
<td>0.040</td>
</tr>
<tr>
<td>20</td>
<td>0.032</td>
<td>0.042</td>
</tr>
<tr>
<td>30</td>
<td>0.033</td>
<td>0.052</td>
</tr>
</tbody>
</table>
Low-cost test platform (test trolley) – v.2

- u-blox antennas (receivers ZED-F9P)
- IMU (xsens MTi-7)
- Geodetic prism
- Applanix mobile mapping system
- Raspberry Pi and others electronic low-cost equipment
- Odometers
- Reference track
- Low-cost track
Combination of different sensors’ parameters

ACCELEROMETER ONLY

GYROSCOPE ONLY (STRAPDOWN INTEGRATION)

KALMAN FILTER TO FUSE ACCELEROMETER AND GYROSCOPE
Integration EKF model (main equations) (1)

\[
x_k^- = \begin{bmatrix} x_k \\ y_k \\ \varphi_k \end{bmatrix} = \begin{bmatrix} x_{k-1} + \cos(\varphi_{k-1}) \cdot (\Delta odo_k + w_{odo}) \\ y_{k-1} + \sin(\varphi_{k-1}) \cdot (\Delta odo_k + w_{odo}) \\ \varphi_{k-1} + (\omega_{gyro,k} + w_{gyro}) \cdot \Delta t \end{bmatrix}
\]

\[
\Phi_{k-1} = \frac{\partial f(x, u, w)}{\partial x} = \begin{bmatrix} 1 & 0 & -\sin(\varphi_{k-1}) \cdot \Delta odo_k \\ 0 & 1 & \cos(\varphi_{k-1}) \cdot \Delta odo_k \\ 0 & 0 & 1 \end{bmatrix}
\]

\[
Q = \begin{bmatrix} \sigma_{odo}^2 & 0 \\ 0 & \sigma_{gyro}^2 \end{bmatrix}; \quad G = \frac{\partial f(x, u, w)}{\partial w} = \begin{bmatrix} \cos(\varphi_{k-1}) & 0 \\ \sin(\varphi_{k-1}) & 0 \\ 0 & \Delta t \end{bmatrix}
\]
Integration EKF model (main equations) (2)

\[
K_k = P_k^{-H^T(HP_k^{-}H^T + R)^{-1}} \\
x_k = x_k^- + K_k(z_k - h(x_k^-)) \\
P_k = (I - K_kH)P_k^-
\]
EKF filter input and reference data

**Input data [50 Hz]**
- GNSS u-blox: X [m], Y [m], \( \phi \) [°]
- IMU xsens: \( \omega \) (z-axis) [rad/s]
- Odometry: \( \Delta s \) [m]

**Reference data**
- Tachimetry [1 Hz]: X [m], Y [m]
- Applanix [200 Hz]: X [m], Y [m], \( \phi \) [°]

Test area - terrace of one of the building UPWr (Wrocław, Poland)
Results (1) – Applanix Mobile Mapping System

<table>
<thead>
<tr>
<th>Direction</th>
<th>Applanix position accuracy [RMS]</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>0.014 m (referenced to the tachimetry)</td>
</tr>
<tr>
<td>East</td>
<td>0.013 m (referenced to the tachimetry)</td>
</tr>
<tr>
<td>Heading</td>
<td>0.1 degree (value after post-processing in POSPac software)</td>
</tr>
</tbody>
</table>
Results (2) – GNSS+IMU+odometry – variant 0

\[
Q = \begin{bmatrix}
\sigma_{odo}^2 & 0 \\
0 & \sigma_{gyro}^2
\end{bmatrix}
\]

\[
R = \begin{bmatrix}
\sigma_{GPS,X}^2 & 0 & 0 \\
0 & \sigma_{GPS,Y}^2 & 0 \\
0 & 0 & \sigma_{GPS,\varphi}^2
\end{bmatrix}
\]

\[\Delta t = 0.02s\]

<table>
<thead>
<tr>
<th>Position from:</th>
<th>Direction</th>
<th>Position accuracy [RMS]</th>
</tr>
</thead>
<tbody>
<tr>
<td>u-blox</td>
<td>North</td>
<td>0.052 m</td>
</tr>
<tr>
<td></td>
<td>East</td>
<td>0.089 m</td>
</tr>
<tr>
<td>sensors fusion (EKF)</td>
<td>North</td>
<td>0.039 m</td>
</tr>
<tr>
<td></td>
<td>East</td>
<td>0.022 m</td>
</tr>
</tbody>
</table>
Results (3) – GNSS+IMU+odometry – variant 1

Position from: Direction Position accuracy [RMS]

<table>
<thead>
<tr>
<th></th>
<th>North</th>
<th>East</th>
</tr>
</thead>
<tbody>
<tr>
<td>u-blox</td>
<td>0.052 m</td>
<td>0.089 m</td>
</tr>
<tr>
<td>sensors fusion (EKF)</td>
<td>0.031 m</td>
<td>0.053 m</td>
</tr>
</tbody>
</table>

\[
Q = \begin{bmatrix}
\sigma^2_{odo} & 0 \\
0 & \sigma^2_{gyro}
\end{bmatrix}
\]

\[
R = \begin{bmatrix}
\sigma^2_{GPS,X} & 0 & 0 \\
0 & \sigma^2_{GPS,Y} & 0 \\
0 & 0 & \sigma^2_{GPS,\phi}
\end{bmatrix}
\]

\[\Delta t = 0.02s\]
Results (4) – GNSS+IMU+odometry – variant 2

Position from: Direction  Position accuracy [RMS]

u-blox  North  0.052 m
         East  0.089 m

sensors fusion (EKF)  North  0.037 m
                      East  0.025 m

\[
Q = \begin{bmatrix}
\sigma_{odo}^2 & 0 \\
0 & \sigma_{gyro}^2
\end{bmatrix}
\]

\[
R = \begin{bmatrix}
\sigma_{GPS,X}^2 & 0 & 0 \\
0 & \sigma_{GPS,Y}^2 & 0 \\
0 & 0 & \sigma_{GPS,\phi}^2
\end{bmatrix}
\]

\[\Delta t = 0.02s + 75\mu s\]
Results (5) – GNSS+IMU+odometry – variant 3

\[ Q = \begin{bmatrix} \sigma_{odo}^2 + 0.3 mm & 0 \\ 0 & \sigma_{gyro}^2 \end{bmatrix} \]

\[ R = \begin{bmatrix} \sigma_{GPS,X}^2 & 0 & 0 \\ 0 & \sigma_{GPS,Y}^2 & 0 \\ 0 & 0 & \sigma_{GPS,\varphi}^2 \end{bmatrix} \]

\[ \Delta t = 0.02 s + 75 \mu s \]

<table>
<thead>
<tr>
<th>Position from:</th>
<th>Direction</th>
<th>Position accuracy [RMS]</th>
</tr>
</thead>
<tbody>
<tr>
<td>u-blox</td>
<td>North</td>
<td>0.052 m</td>
</tr>
<tr>
<td></td>
<td>East</td>
<td>0.089 m</td>
</tr>
<tr>
<td>sensors fusion (EKF)</td>
<td>North</td>
<td>0.026 m</td>
</tr>
<tr>
<td></td>
<td>East</td>
<td>0.019 m</td>
</tr>
</tbody>
</table>
Results (6) – GNSS+IMU+odometry sensors fusion (final result)

uBlox - RMS:
N = 0.052 m
E = 0.089 m

EKF - RMS:
N = 0.039 m
E = 0.021 m

variant 0

EKF - RMS:
N = 0.026 m
E = 0.019 m

variant 3
Results (7) – GNSS heading and IMU sensors fusion

<table>
<thead>
<tr>
<th>Heading from:</th>
<th>Heading accuracy [RMS]</th>
</tr>
</thead>
<tbody>
<tr>
<td>two GNSS antennas (u-blox)</td>
<td>5.55 [°]</td>
</tr>
<tr>
<td>sensors fusion (EKF)</td>
<td>0.59 [°]</td>
</tr>
</tbody>
</table>
Results (8) – GNSS heading and IMU sensors fusion (final result)
Conclusions

• After integration, we obtained almost two times better results for position and orientation than without integration.
• It should be noted that the precise time synchronization between the sensors is very important.

Further work will be focused on improving hardware:
◦ synchronization sensors using a signal from 1PPS pin from ublox module or using synchronization option built in xsens module,
◦ adding to the filter another dimension (2D -> 3D).
Thank you for your attention!
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