Wrocław University of Environmental and Life Sciences

Real-Time fusion of sensors for navigation

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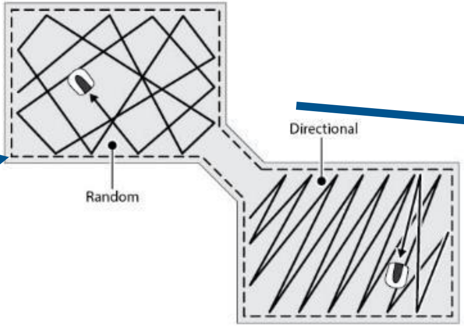
Outline

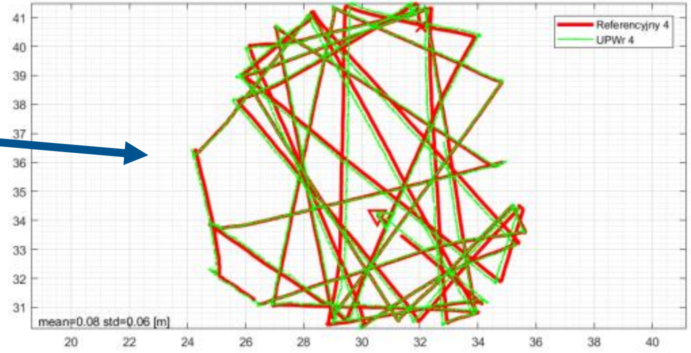
1. Introduction and motivation
2. Low-cost test platform (test trolley)
3. Integration extended Kalman Filter model
4. EKF filter input and reference data
5. Results
6. Conclusion

Introduction and motivation (1)

Autonomous lawnmower **with** border cable



https://powerequipment.honda.com/

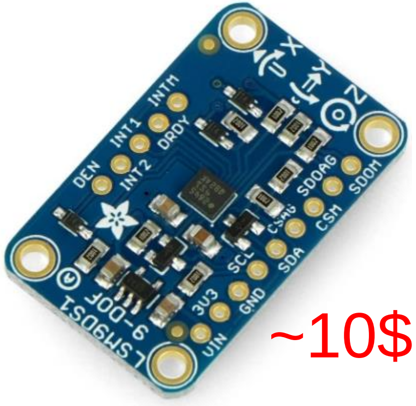


Autonomous lawnmower **without** border cable

http://grauonline.de/cms2/?page_id=153

Introduction and motivation (2)

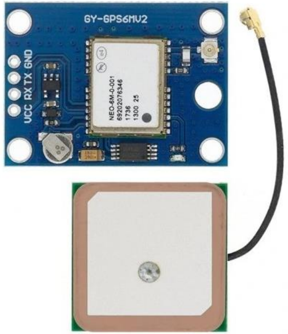
IMU



~10$

~550$

GNSS



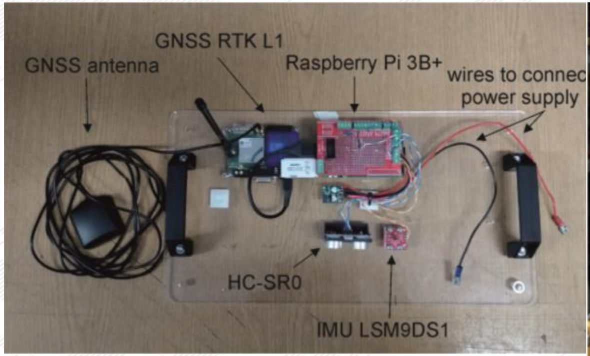
~10$

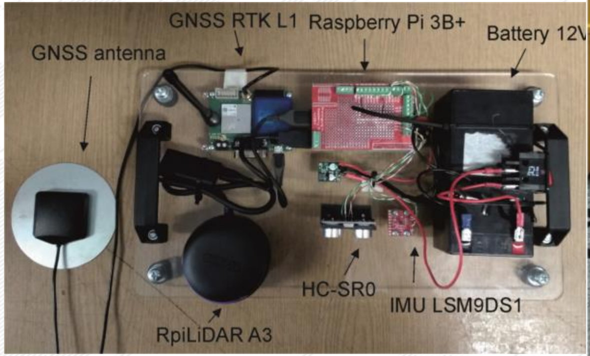
~250$

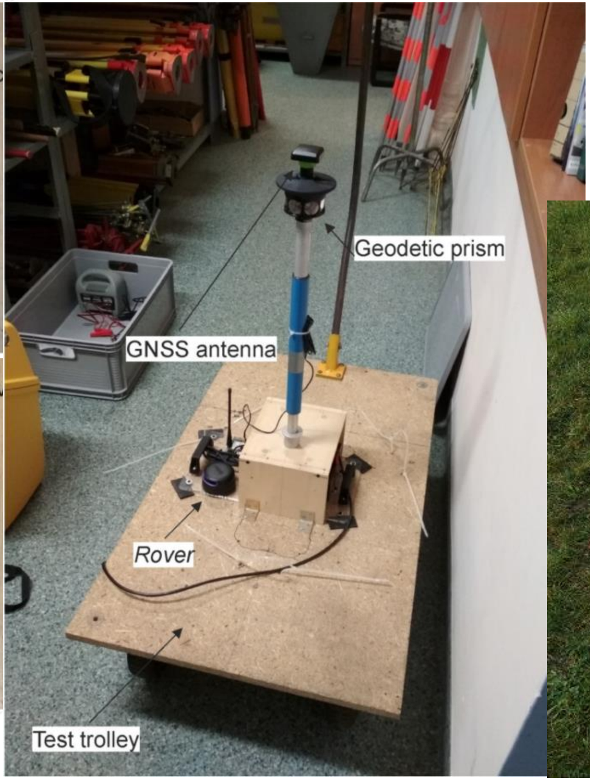
Hi-end Mobile Mapping System

~50000$ - ...

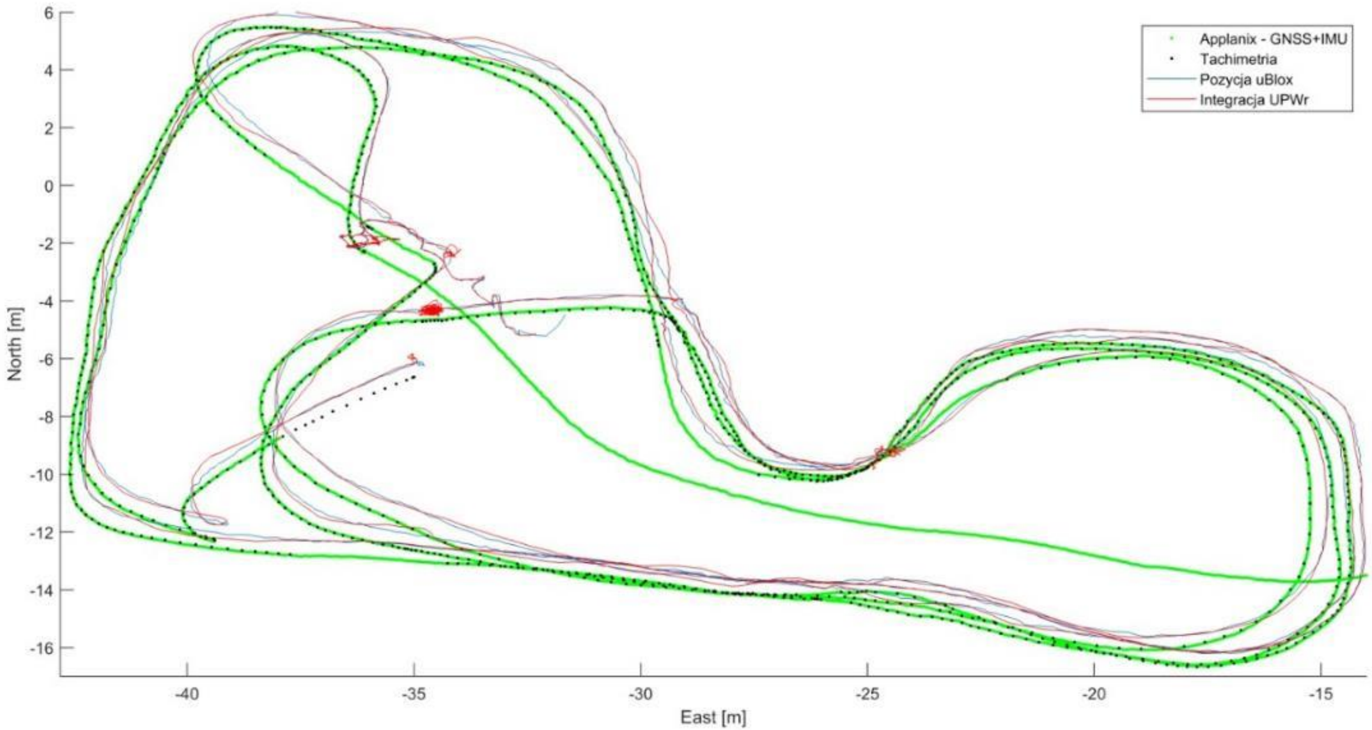
Low-cost test platform (test trolley) – v.1







The first EKF results using test platform version 1

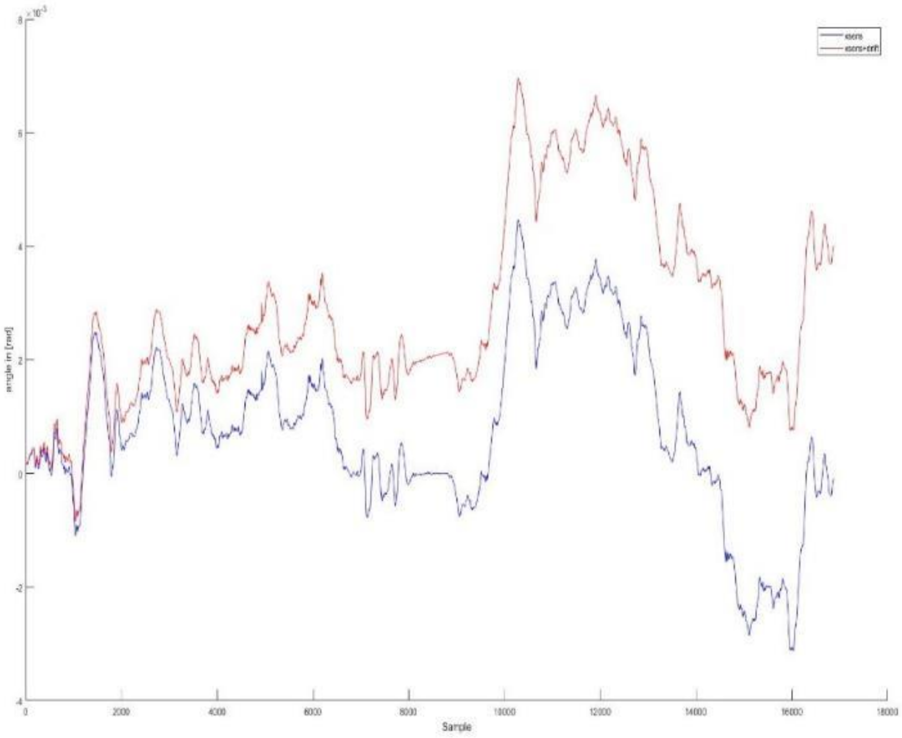


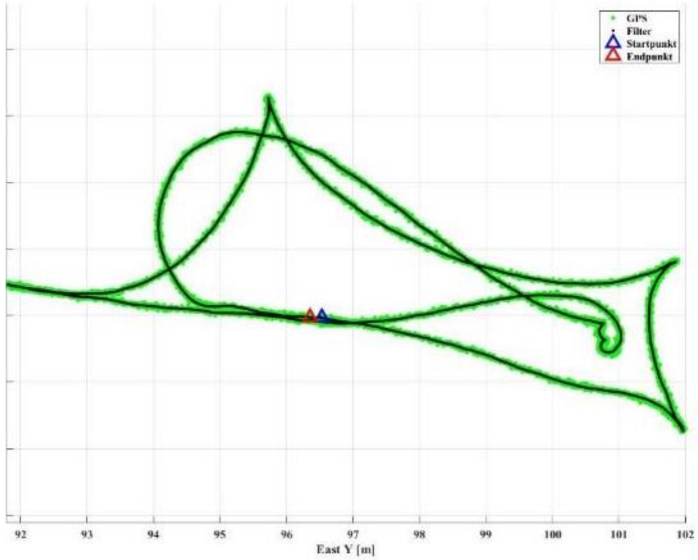
EKF - RMS:

N = 0.25 m

E = 0.28 m

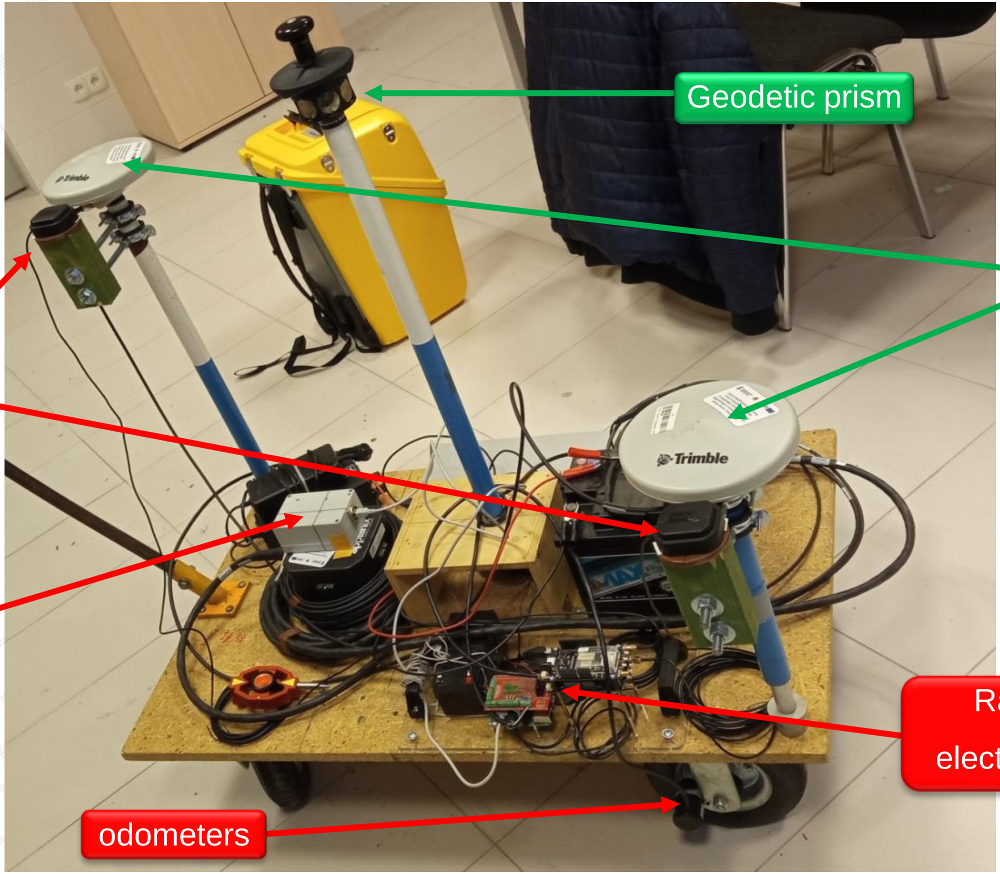
Sensors fusion and test data



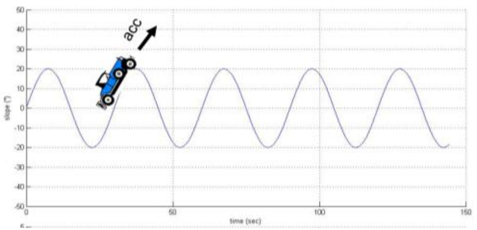


Drift (°/h)	IMU – fiber optic (0.1°/h)		Xsens - MEMS (10°/h)	
	N - RMS [m]	E - RMS [m]	N - RMS [m]	E - RMS [m]
0	0.029	0.042	0.029	0.042
10	0.029	0.040	0.029	0.040
20	0.032	0.042	0.032	0.041
30	0.033	0.052	0.033	0.053

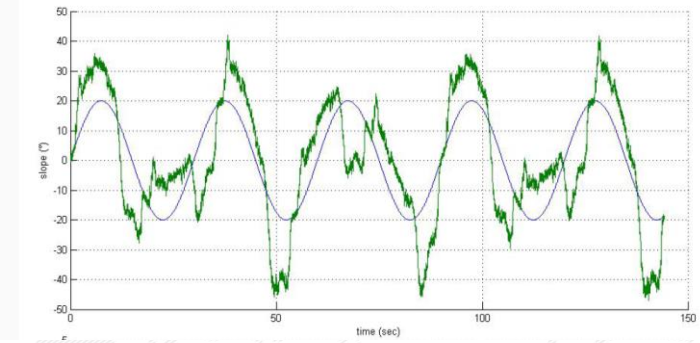
Low-cost test platform (test trolley) – v.2



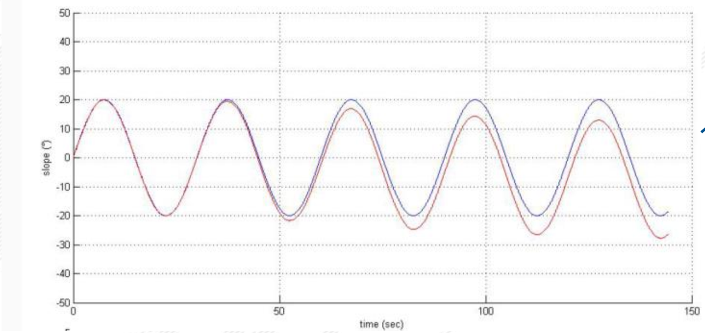
Combination of different sensors' parameters



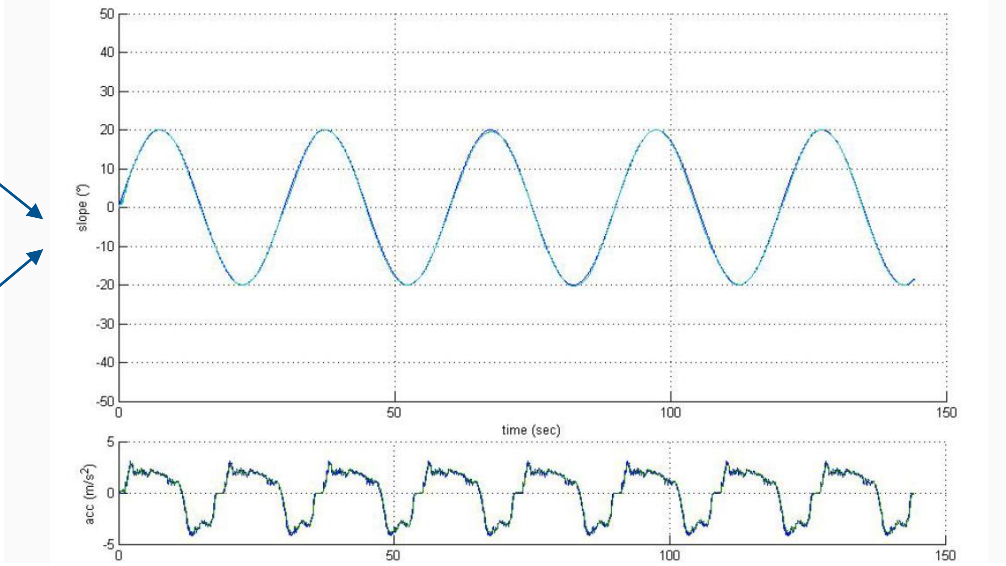
ACCELEROMETER ONLY



GYROSCOPE ONLY (STRAPDOWN INTEGRATION)



KALMAN FILTER TO FUSE ACCELEROMETER AND GYROSCOPE



Integration EKF model (main equations) (1)

$$x_k^- = f(x_{k-1}, u_k, w_k)$$
$$P_k^- = \Phi P_{k-1} \Phi^T + GQG^T$$

Prediction

State vector

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

Transition matrix

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

System noise

$$Q = \begin{bmatrix} \sigma_{odo}^2 & 0 \\ 0 & \sigma_{gyro}^2 \end{bmatrix}; \; G = \frac{\partial f(x,u,w)}{\partial w} = \begin{bmatrix} cos(\varphi_{k-1}) & 0 \\ sin(\varphi_{k-1}) & 0 \\ 0 & \Delta t \end{bmatrix}_{x=x_{k-1}, u=u_{k-1}}$$

Integration EKF model (main equations) (2)

$$K_k = P_k^- H^T (H P_k^- H^T + R)^{-1}$$
$$x_k = x_k^- + K_k(z_k - h(x_k^-))$$
$$P_k = (I - K_k H) P_k^-$$

Update

$$z_k = \begin{bmatrix} x_{GPS,k} \\ y_{GPS,k} \\ \varphi_{GPS,k} \end{bmatrix}$$

Measurement vector

$$R = \begin{bmatrix} \sigma^2_{GPS,X} & 0 & 0 \\ 0 & \sigma^2_{GPS,Y} & 0 \\ 0 & 0 & \sigma^2_{GPS,\varphi} \end{bmatrix}$$

Measurement noise

EKF filter input and reference data

Input data [50 Hz]

GNSS u-blox:
X [m], Y [m], φ [^{0}]

IMU xsens:
ω (z-axis) [rad/s]

odometry:
Δs [m]

Reference data

Tachimetry [1 Hz]:
X [m], Y [m]

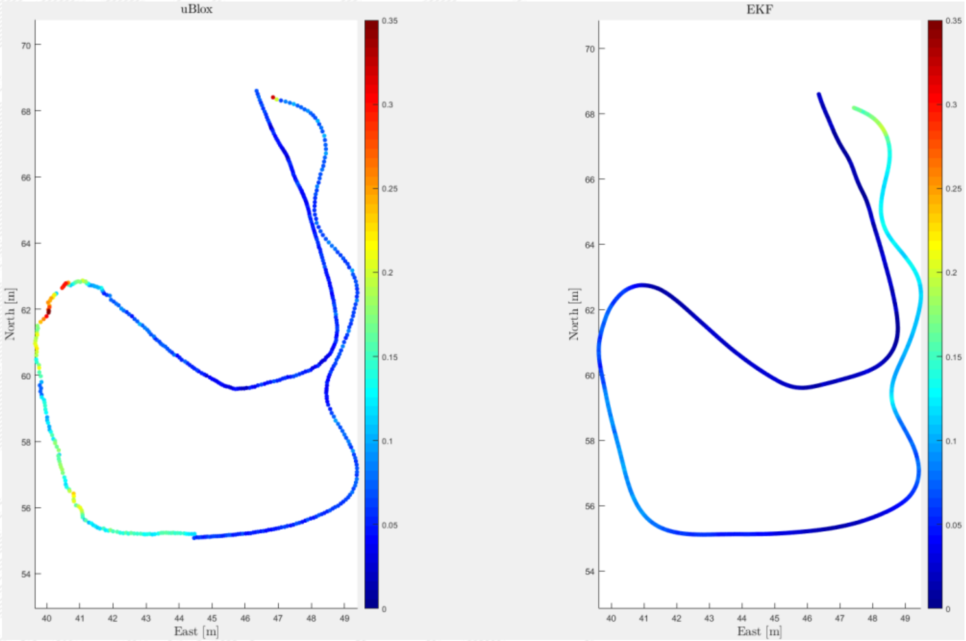
Applanix [200 Hz]:
X [m], Y [m], φ [^{0}]

Test area - terrace of one of the building UPWr (Wrocław, Poland)

Results (1) – Applanix Mobile Mapping System

Direction	***Applanix position accuracy [RMS]***
North	**0.014 m** (referenced to the tachimetry)
East	**0.013 m** (referenced to the tachimetry)
Heading	**0.1 degree** (value after post-processing in POSPac software)

Results (2) – GNSS+IMU+odometry – variant 0



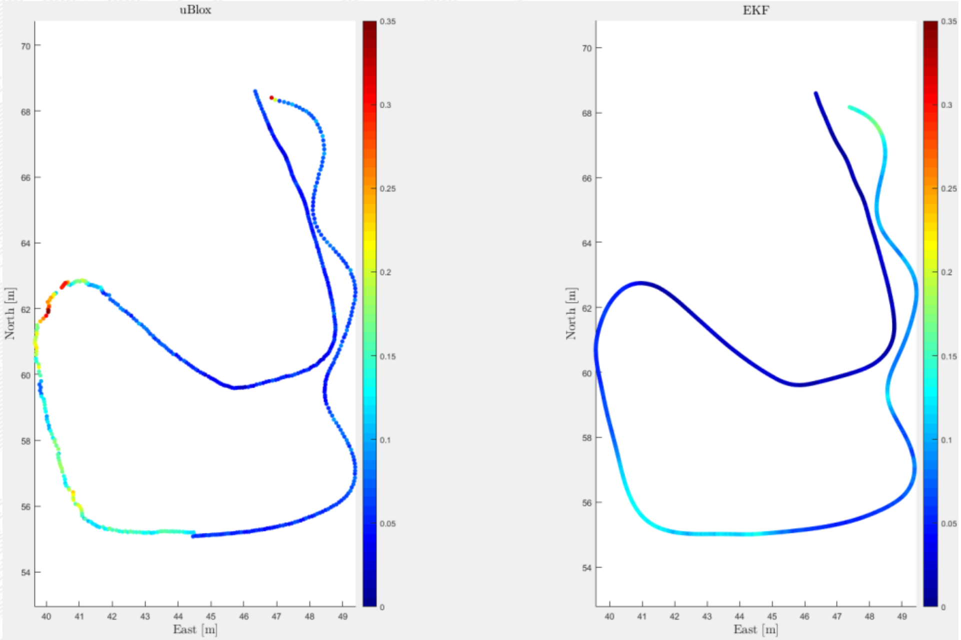
$$Q = \begin{bmatrix} \sigma_{odo}^2 & 0 \\ 0 & \sigma_{gyro}^2 \end{bmatrix}$$

$$R = \begin{bmatrix} \sigma_{GPS,X}^2 & 0 & 0 \\ 0 & \sigma_{GPS,Y}^2 & 0 \\ 0 & 0 & \sigma_{GPS,\varphi}^2 \end{bmatrix}$$ Const.

$$\Delta t = 0.02s$$

Position from:	Direction	Position accuracy [RMS]
u-blox	North East	0.052 m 0.089 m
sensors fusion (EKF)	North East	**0.039 m** **0.022 m**

Results (3) – GNSS+IMU+odometry – variant 1



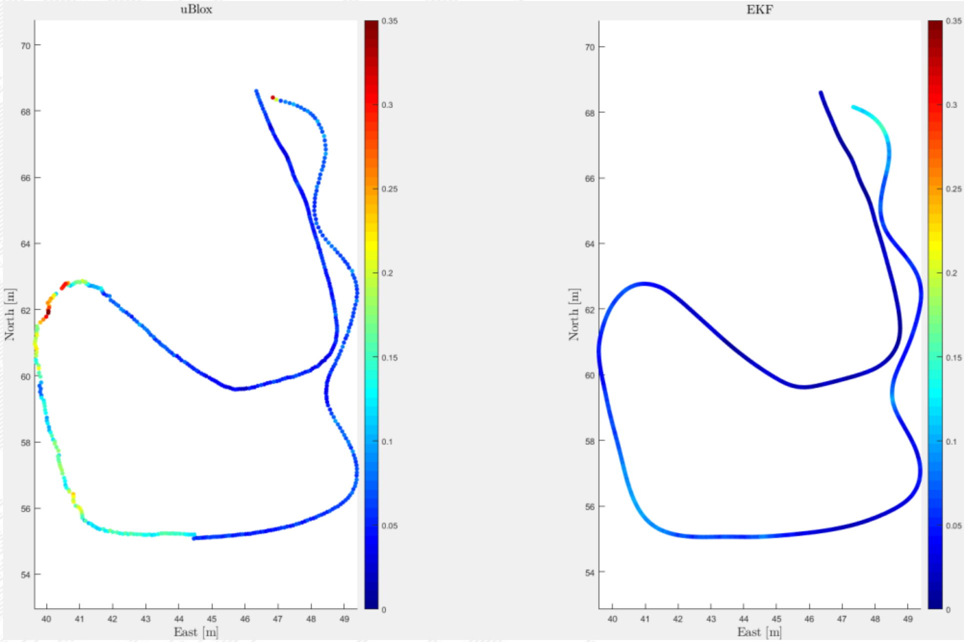
$$Q = \begin{bmatrix} \sigma_{odo}^2 & 0 \\ 0 & \sigma_{gyro}^2 \end{bmatrix}$$

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

$$\Delta t = 0.02s$$

Position from:	Direction	Position accuracy [RMS]
u-blox	North	0.052 m
	East	0.089 m
sensors fusion (EKF)	North	**0.031 m**
	East	**0.053 m**

Results (4) – GNSS+IMU+odometry – variant 2



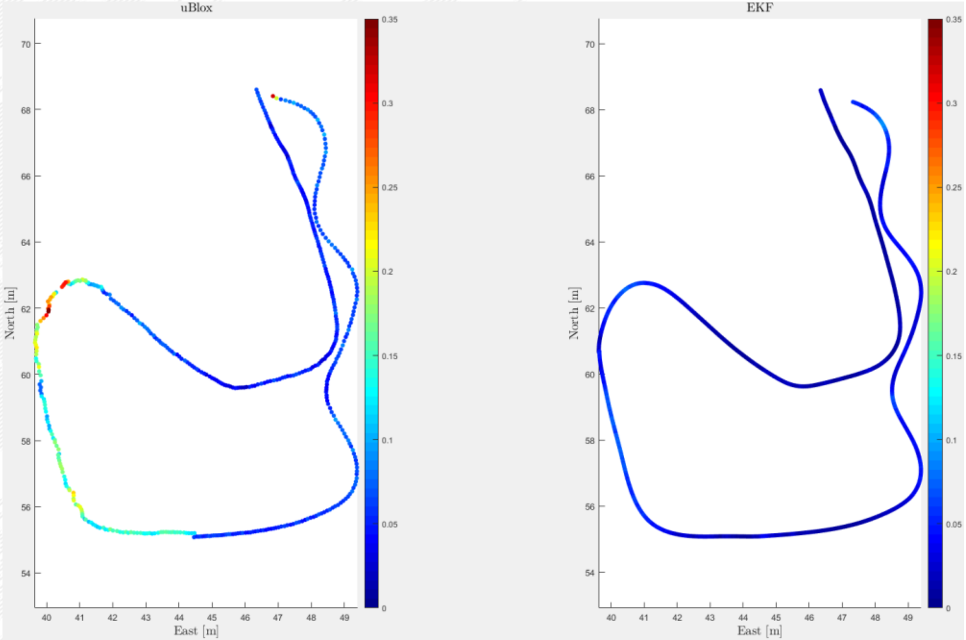
$$Q = \begin{bmatrix} \sigma_{odo}^2 & 0 \\ 0 & \sigma_{gyro}^2 \end{bmatrix}$$

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

$$\Delta t = 0.02s + 75\mu s$$

Position from:	Direction	Position accuracy [RMS]
u-blox	North East	0.052 m 0.089 m
sensors fusion (EKF)	North East	**0.037 m** **0.025 m**

Results (5) – GNSS+IMU+odometry – variant 3



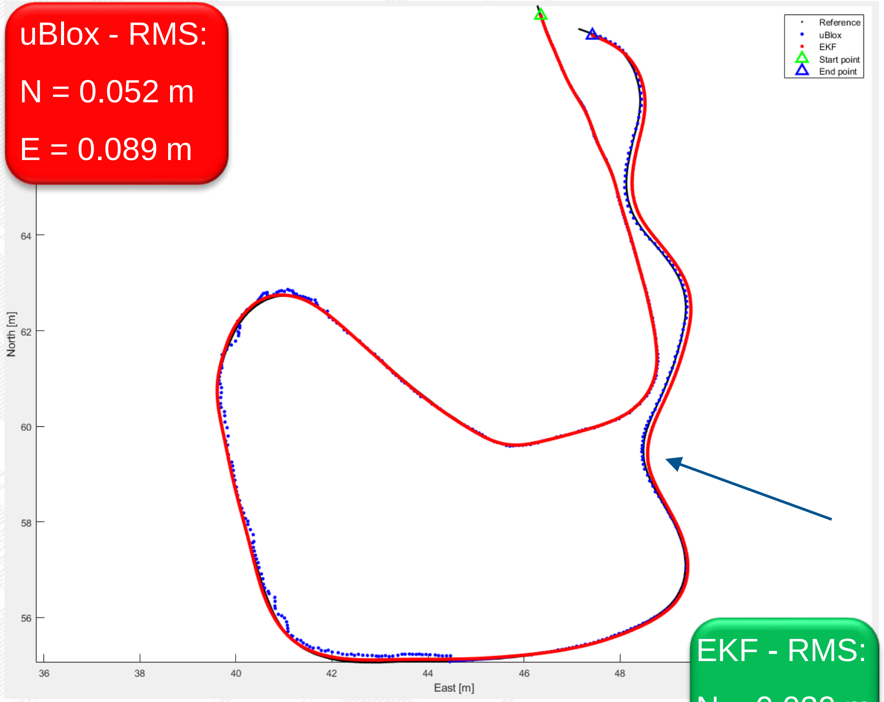
$$Q = \begin{bmatrix} \sigma_{odo}^2 + \mathbf{0.3mm} & 0 \\ 0 & \sigma_{gyro}^2 \end{bmatrix}$$

$$R = \begin{bmatrix} \sigma_{GPS,X}^2 & 0 & 0 \\ 0 & \sigma_{GPS,Y}^2 & 0 \\ 0 & 0 & \sigma_{GPS,\varphi}^2 \end{bmatrix}$$ **dynamic**

$$\Delta t = 0.02s + \mathbf{75\mu s}$$

Position from:	Direction	Position accuracy [RMS]
u-blox	North East	0.052 m 0.089 m
sensors fusion (EKF)	North East	**0.026 m** **0.019 m**

Results (6) – GNSS+IMU+odometry sensors fusion (final result)



uBlox - RMS:

N = 0.052 m

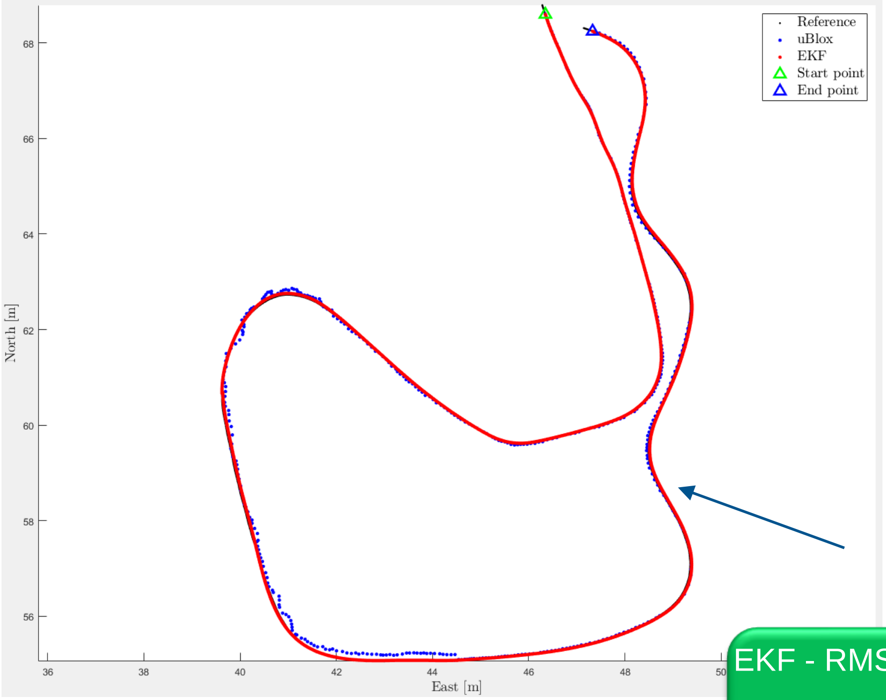
E = 0.089 m

EKF - RMS:

N = 0.039 m

E = 0.021 m

variant 0



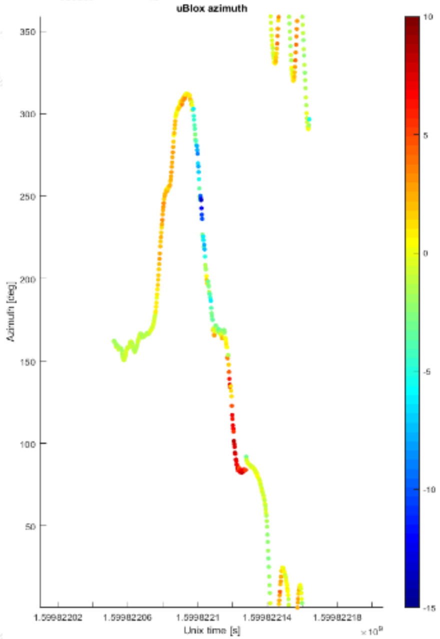
EKF - RMS:

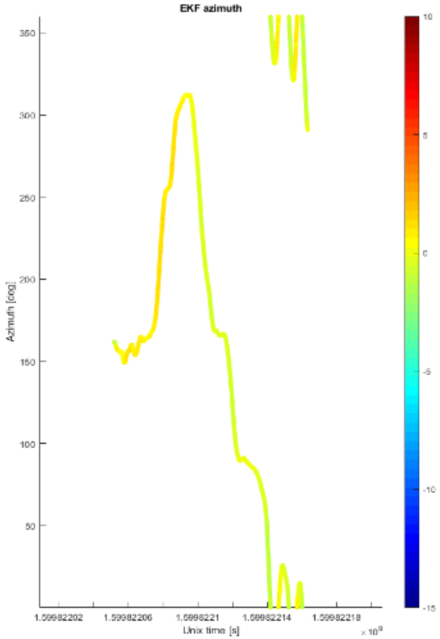
N = 0.026 m

E = 0.019 m

variant 3

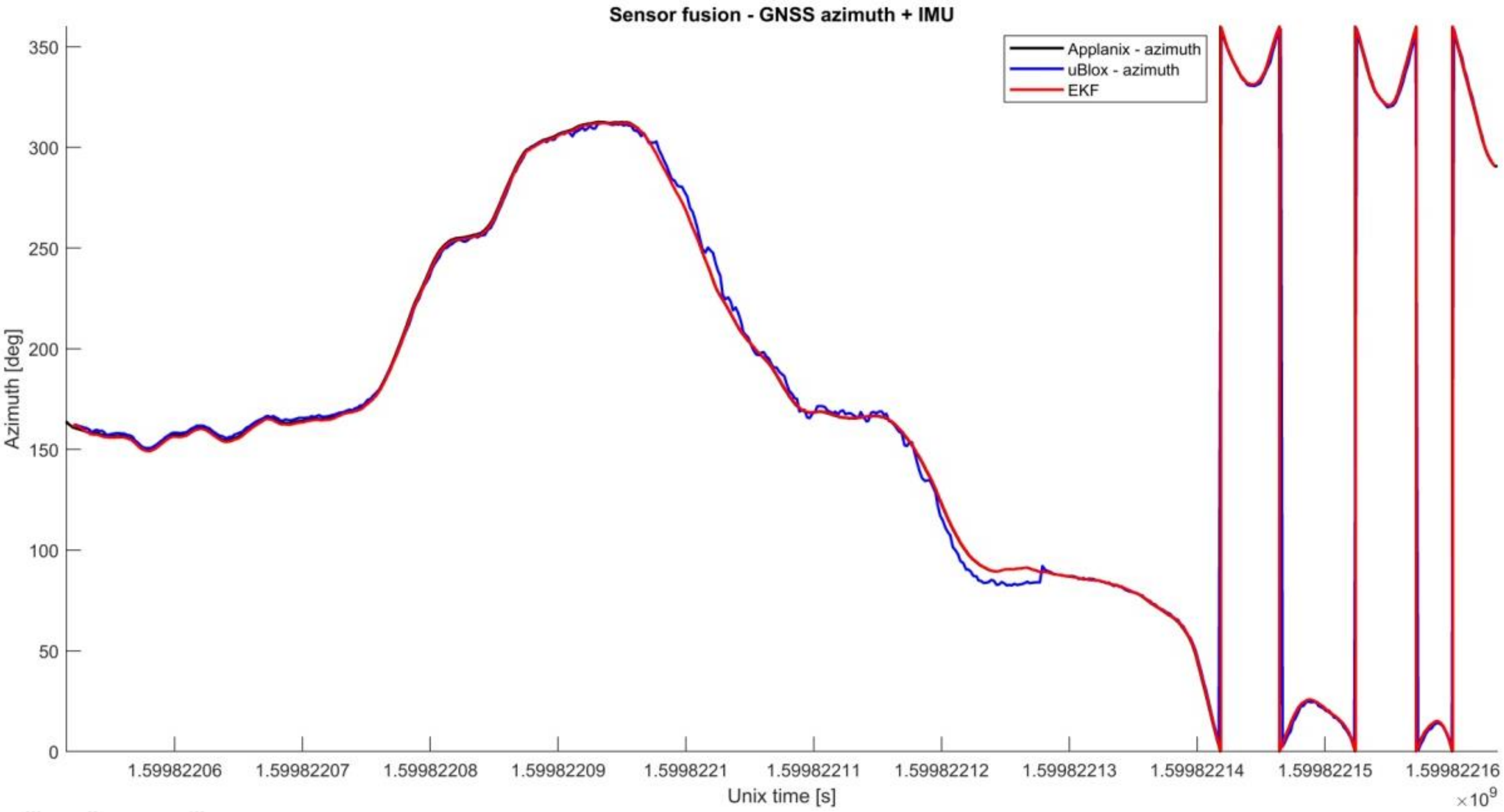
Results (7) – GNSS heading and IMU sensors fusion





Heading from:	Heading accuracy [RMS]
two GNSS antennas (u-blox)	5.55 [º]
sensors fusion (EKF)	0.59 [º]

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).

Uniwersytet Przyrodniczy we Wrocławiu

Thank you for your attention!

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