Chair of Flight Measuring Technology
University of Stuttgart
Pfaffenwaldring 31, 70569 Stuttgart, Germany

IPIN competition 2024

Description of the competing system

The competing software system represents a ZUPT (Zero Velocity Update) based pedestrian inertial navigation system (INS) with its focus on inertial sensor data without relying on GNSS measurements for aiding. The system uses a total-state, continuous-discrete extended Kalman Filter, which includes inertial sensor bias estimation and employs a Runge-Kutta algorithm of fourth order. The system furthermore includes earth's rotation rate in the mechanization equations and applies gyrocompassing techniques in an initial alignment process within the scope of possibilities of the competition. Within these scopes, additional aiding techniques might be utilised (will show after processing the “Testing Trial”).

Navigation or position estimation of the competing system mainly uses two coordinate systems, as depicted in Fig. 1. Navigation itself takes place in the gravity-fixed navigation system *n*, which represents a Cartesian north-east-down system with coordinate axes ${}_nx$, ${}_ny$, and ${}_nz$. The body coordinate system *b* represents the ULISS unit (i.e. the data generating unit of the competition) at its origin and has the coordinate axes ${}_bx$, ${}_by$, and ${}_bz$ aligned according to Fig. 1. The origin of the navigation coordinate system is calculated according to the WGS84 coordinates, given by Key Point n°1 and the resulting position estimates of the competing software are transferred vice versa to WGS84 coordinates. The initial yaw angle of the *b* system is assumed so that ${}_bx$ is pointing towards Key Point n°2 whereas the initial roll and pitch angle are calculated via tilt-sensing with the first set of accelerometer data.

Fig. 2 depicts the system structure (total state Kalman Filter) of the competing system. The moving object (i.e. the ULISS measurement unit) is represented by block 1 with its state vector

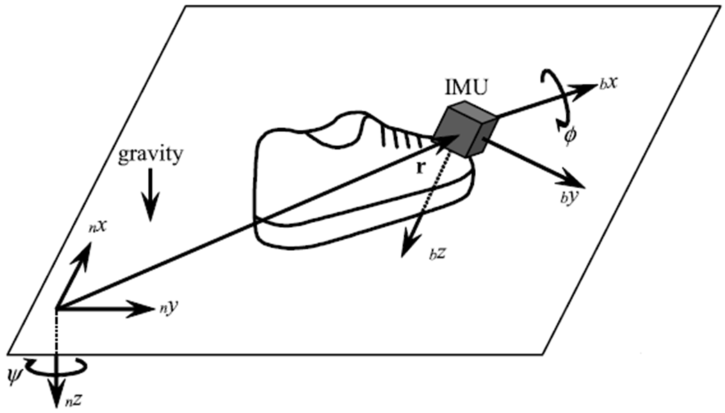

Figure 1. Relevant coordinate systems in competing system

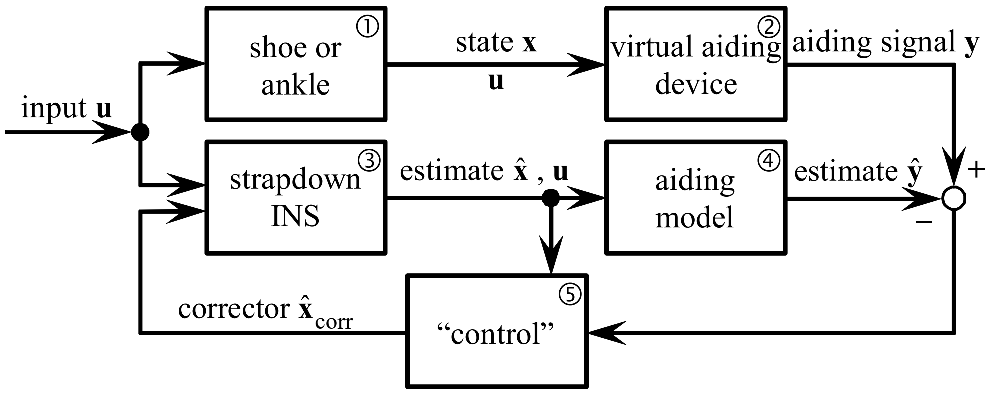

Figure 2. Simplified system structure for competing system

$$\mathbf{x}(t) = \begin{bmatrix} \text{position vector } {}_n\mathbf{r} \\ \text{velocity vector } {}_n\mathbf{v} \\ \text{attitude quaternion } {}_n\mathbf{q} \\ \text{3 accelerometer bias } {}_b\mathbf{b}_a \\ \text{3 gyroscope bias } {}_b\mathbf{b}_\omega \end{bmatrix}.$$

The input $\mathbf{u}$ is captured by the IMU and delivers the sensor reading

$$\mathbf{u}(t) = \begin{bmatrix} \text{acceleration vector } \mathbf{a} \\ \text{angular rate vector } \boldsymbol{\omega} \end{bmatrix}.$$

The aiding vector $\mathbf{y}$ (originating from block 2) in the case of ZUPT aiding contains pseudo measurements of zero velocity and is given by

$$\mathbf{y}(t) = [\text{velocity vector } \mathbf{v} = \mathbf{0}].$$

Stance phases, in which ZUPT aiding is applied, are detected by processing the input data with a stance hypothesis optimal detector (SHOE [1]).

Block 3 contains a set of ordinary, coupled, and nonlinear differential equations for the derivative of the state estimate

$$\dot{\hat{\mathbf{x}}} = \mathbf{f}(\hat{\mathbf{x}}, \mathbf{u})$$

which are solved for $\hat{\mathbf{x}}$ with a Runge-Kutta algorithm of fourth order. Based on the current state estimate, the aiding estimate is evaluated in block 4 by

$$\hat{\mathbf{y}} = \mathbf{f}(\hat{\mathbf{x}}, \mathbf{u}),$$

which simplifies to $\hat{\mathbf{y}} = \hat{\mathbf{v}}$ and $\mathbf{y} = \mathbf{0}$ in the case of ZUPT. The corrector term $\hat{\mathbf{x}}_{\mathrm{corr}}$ for the state estimate is calculated according to a continuous-discrete Kalman Filter by

$$\hat{\mathbf{x}}_{\mathrm{corr}} = \mathbf{K}(\mathbf{y} - \hat{\mathbf{y}}),$$

with the Kalman gain matrix being

$$\mathbf{K} = \mathbf{P}\mathbf{H}^{\mathrm{T}}(\mathbf{H}\mathbf{P}\mathbf{H}^{\mathrm{T}} + \mathbf{R})^{-1}$$

and the error covariance matrix $\mathbf{P}$ being propagated according to

$$\dot{\mathbf{P}} = \mathbf{F}\mathbf{P} + \mathbf{P}\mathbf{F}^{\mathrm{T}} + \mathbf{G}\mathbf{Q}\mathbf{G}^{\mathrm{T}}$$

and a Runge-Kutta algorithm of fourth order. In the aforementioned equations, $\mathbf{Q}$ is the covariance matrix of the system input noise, $\mathbf{G}$ accounts for model errors as well as errors introduced by the system input noise, and $\mathbf{R}$ is the covariance matrix of the measurement noise (block 5) [2].

To further enhance the estimation of the gyroscope bias ${}_{b}\mathbf{b}_{\omega}$, which is one of the most dominant error sources in inertial navigation, an additional alignment process is applied. With the confirmed gyrocompassing abilities of even low-cost IMUs (to some extent) [3], the aiding vector can be extended to

$$\mathbf{y}_{\mathrm{alignment}}(t) = \begin{bmatrix} {}_{n}\mathbf{r} \\ {}_{n}\mathbf{\Theta} \\ {}_{n}\boldsymbol{\omega}_{\mathrm{ie}} \end{bmatrix}$$

during the alignment phase, with the known position ${}_{n}\mathbf{r}$, attitude ${}_{n}\mathbf{\Theta}$ (in Euler angles), and earth's rotation ${}_{n}\boldsymbol{\omega}_{\mathrm{ie}}$. In the competition, the entries of the alignment vector are calculated according to the initial position and attitude (as described above) with the information given for Key Points n°1 and n°2. The alignment process will take place from the beginning of the Scoring Trial until movement is detected (by the first non-ZUPT phase). With the sensor being sufficiently at rest and the alignment process being sufficiently long, the bias estimation and thus the state estimates can be improved.

With the availability of pressure and sensor data, a barometric altitude formula is implemented to provide additional aiding for the height of the system.

At the state of application, it is additionally considered to add GNSS aiding to support the alignment and initial phase of the Scoring Trial in moments where a sufficient number of satellite signals are available and the system is deemed outside a building.

References:

[1] I. Skog, J.-O. Nilsson, and P. Handel, ``Evaluation of zero-velocity detectors for foot-mounted inertial navigation systems," in *Proc. Int. Conf. Indoor Positioning Indoor Navigat.*, Zurich, Switzerland, Sep. 2010, pp. 1-6, doi: 10.1109/IPIN.2010.5646936.

[2] J. F. Wagner, M. Kohl and B. Györfi, "Reevaluation of Algorithmic Basics for ZUPT-Based Pedestrian Navigation," in *IEEE Access*, vol. 10, pp. 118419-118437, 2022, doi: 10.1109/ACCESS.2022.3220629.

[3] B. Györfi, M. Kohl and J. F. Wagner, "Comparison of the North Finding Capability of several MEMS IMUs of Different Performance Grades," *2023 DGON Inertial Sensors and Systems (ISS)*, Braunschweig, Germany, 2023, pp. 1-22, doi: 10.1109/ISS58390.2023.10361926.