UDOKS Project: Development of a Pedestrian Navigation System With Multiple Integrated Sensors

Serkan Zobar [1,2] and Mehmet Çiydem [2]

[1] *Defence Systems Technologies Business Sector, ASELSAN Inc., 06200 Ankara, Turkey*
[2] *Department of Electrical and Electronics Engineering, Gazi University, 06570 Ankara, Turkey*

Abstract

In both civilian and military areas, accurate and robust navigation systems have become a critical tool for positioning and tracking capabilities of pedestrians under Global Navigation Satellite Systems (GNSS)-denied conditions, e.g., underground workers, dismounted soldiers on battlefield, and first responders within a building. In order to navigate through these harsh environments, pedestrian navigation systems (PNSs) with multiple integrated sensors are indispensable. In the research project which is funded by ASELSAN and entitled "Positioning in GNSS Denied Environments (labeled as UDOKS)", we are working on the development of a PNS integrating inertial sensors (i.e., gyroscopes and accelerometers), Ultra-Wideband (UWB) ranging sensors, and aiding sensors such as magnetometers and a barometer. Furthermore, a simulation environment dedicated to PNSs with multiple integrated sensors is being implemented as a part of UDOKS project. The simulation environment will allow the user to compare several pedestrian navigation algorithms which are based on different types of sensor technologies and different levels of sensor errors. Moreover, the simulation environment will be used as a means to test and evaluate new strategies and approaches on pedestrian navigation during algorithm and configuration design phase. The simulation environment will have an open and modular architecture so that it will be capable of inserting and integrating complementary navigation algorithms and sensor technologies. This open and modular architecture of the simulation environment will provide a huge potential benefit to design PNSs especially for the needs in various GNSS-denied applications and usage scenarios.

This Work-in-Progress (WiP) paper provides a high-level description of the PNS being developed and a general outline of the simulation environment being implemented in UDOKS project. Furthermore, preliminary indoor performance results of the pure inertial sensors-based PNS (i.e., utilizing only gyroscope and accelerometer measurements) developed as a single navigation system are given.

Keywords

Pedestrian navigation, sensor integration, open and modular architecture

1. Introduction

Over the last three decades, Global Navigation Satellite Systems (GNSS) have become the main positioning and navigation tool for most applications in both civilian and military areas. However, GNSS may not be accessible or practicable in some environments such as indoors, below the ground level, and dense urban areas [1]. To obtain positioning and navigation solutions in such GNSS-denied environments, integration of multiple sensors is inevitable. Of course, the selection of appropriate sensors to integrate depends mainly on the requirements of the application and the knowledge of the usage scenario. Specifically, body-worn pedestrian navigation systems (PNSs) require low size, weight, power and cost (SWaP-C) sensors while the performance accuracy still meets the application's

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EMAIL: szobar@aselsan.com.tr (S. Zobar); mehmetciydem@gazi.edu.tr (M. Çiydem)
ORCID: 0000-0001-5731-7955 (S. Zobar); 0000-0001-9164-8491 (M. Çiydem)

requirements. Therefore, the development of a PNS can be made possible by intelligent methods and algorithms with the ability to address the sensor errors and to reduce their adverse effects on the navigation performance.

1.1. Related works

Pedestrian navigation technologies used for achieving reliable positioning in GNSS-denied environments can be classified into two categories [2]: infrastructure-free and infrastructure-based technologies.

The infrastructure-free technologies depend only on inbuilt sensors. They do not rely on any external infrastructure pre-installed in the environment. Among these technologies, inertial sensors, i.e., gyroscopes and accelerometers, are the most common ones [3]. Using the motion information measured by body-mounted inertial sensors, the pedestrian's position relative to the starting point can be estimated [4-9]. The latest advances especially in Micro Electro-Mechanical System (MEMS)-based inertial sensor technology have brought huge profits to develop PNSs utilizing SWaP-C sensors. A big drawback of inertial sensors-based PNSs is that the positioning error unavoidably increases with time due to noise and biases on the sensor measurements [10]. The inertial sensors of a PNS can be assisted by some other sensors such as magnetometers [11], barometers [12], pressure gauges [13], ultrasonic sensors [14] and radars [15] in order to enhance the accuracy of the position estimation. However, this aiding makes the PNS more complex and more delicate against some environmental conditions (e.g., magnetometer aiding fails in environments with serious magnetic field disturbances). As another infrastructure-free technology, vision-based sensors (cameras) have become an attractive alternative for pedestrian positioning and navigation in recent years [16]. Vision-based navigation systems use cameras to apply visual odometry to estimate the trajectory of the camera using only a stream of images [17].

The infrastructure-based technologies rely on devices or facilities installed in the environment in advance and include Radio Frequency Identification (RFID) [18], Wireless Fidelity (Wi-Fi) [19], Ultra Wideband (UWB) [20], and Bluetooth Low Energy (BLE) [21] technologies. These technologies provide distance- or angle-related measurements for position estimation such as Received Signal Strength Indicator (RSSI), Time of Arrival (ToA), Time Difference of Arrival (TDoA), and Angle of Arrival (AoA) [22]. Pre-installing the infrastructure for these technologies is a costly task. In addition to the high cost, in case of infrastructure failure, the positioning or navigation systems based solely on these technologies fail.

In order to overcome the limitations of each technology briefly described above and to improve the positioning accuracy of the navigation, the integration of multiple sensors is unavoidable. More recently, many multi-sensor PNSs have been developed experimentally and commercially [23-27].

Regarding the PNSs, the implementation of a simulation environment is a major step forward to design and evaluation of the algorithms and sensor integration approaches. In the literature, there are a few studies in the field of PNS simulators [28-31], and there is still a long way to go [32].

1.2. Motivation and novelty

In ASELSAN's self-funded research project entitled "Positioning in GNSS Denied Environments (labeled as UDOKS)", we aim to develop seamless navigation systems for pedestrians in GNSS-denied environments. To achieve this aim, among alternative sensor technologies, inertial sensors (i.e., gyroscopes and accelerometers), UWB ranging sensors, and aiding sensors such as magnetometers and barometers are taken into consideration to integrate. Furthermore, as a part of UDOKS project, a simulation environment allowing the user to evaluate PNSs integrating not only the aforementioned sensor technologies but also other alternatives is being implemented.

The idea in UDOKS project is to assist the inertial and aiding sensors-based PNS with UWB range estimates not only in environments with pre-installed infrastructures (via UWB absolute positioning solutions) but also in environments where such an infrastructure is not available (via UWB relative positioning solutions). Additionally, to the best of the authors' knowledge, there has not been any other simulation environment in the literature for the aim of the design and evaluation of PNSs which is more comprehensive than that being implemented in UDOKS project and outlined generally in this Work-in-Progress (WiP) paper.

The remainder of the paper is organized as follows: The criteria for the selection of sensors to be integrated and the sensor integration concept of the PNS being developed in UDOKS project are described in Section 2. The architectural details of the simulation environment are provided in Section 3. Preliminary indoor performance results of the pure inertial sensors-based PNS developed as a single navigation system are given in Section 4. Finally, the paper is concluded in Section 5.

2. Pedestrian navigation system being developed in UDOKS project

The next subsections describe the criteria for the choice of the sensors to be included by the PNS being developed in UDOKS project and their integration concept.

2.1. Choice of the sensors

Inertial Navigation Systems (INSs) are well-suited for pedestrian navigation purposes in GNSS-denied environments. An INS is composed of a computational unit and an Inertial Measurement Unit (IMU) which typically consists of 3-axis gyroscopes to measure angular rates and 3-axis accelerometers to measure specific forces. The main problem with INSs is that they suffer from integration drift. When using inertial sensors for calculating orientation, velocity and position, the inertial sensor measurements are integrated. These integrations cause any error in the sensor measurements to accumulate over time and create drifts in navigation estimates. Due to this inherent drift problem, the performance of an inertial sensors-based PNS relies deeply on having effective methods for drift correction, and integrating aiding sensors and drift-free absolute positioning systems other than GNSS in GNSS-denied environments. Nowadays, in addition to gyroscopes and accelerometers, the sensor combination in an IMU is generally augmented with 3-axis magnetometers and a barometer which are used for aiding the heading and altitude estimates, respectively. One way to correct the integration drift in an inertial sensors-based PNS is strapping the IMU down to the pedestrian's foot and introducing Zero Velocity Updates (ZUPTs) [33] to the INS mechanization during standstill periods of foot motion. Other drift correction methods, e.g., Zero Angular Rate Update (ZARU) [34] and Heuristic Drift Reduction (HDR) [35], are also available and they will be taken into account in our studies. Tactical and industrial grade foot-mounted IMUs will be employed as the heart of the PNS which is being developed in UDOKS project.

In addition to the foot-mounted IMU and aiding sensors such as magnetometers and a barometer, Ultra Wideband (UWB) ranging sensors will be used in UDOKS project as a complementary sensor technology for providing drift-free absolute position values. UWB, among Radio Frequency (RF) technologies, is the most promising one due to its range estimation capability much more precise than of others such as Wi-Fi and Bluetooth Low Energy (BLE) [36]. Large bandwidth of UWB signals brings many advantages for positioning such as penetration through obstacles and immunity to multipath fading [37]. Moreover, UWB technology allows simultaneous position and data transmission, and combines remarkable features concerning size and power consumption [38]. To perform absolute positioning with UWB sensors, a global or local reference coordinate system must be created and absolute position of each UWB sensor must be described with respect to this reference coordinate system. The reference coordinate system is developed by using UWB sensors referred to as anchors. The initial position assignment of anchors can be done by placing them on positions with known coordinates or on positions with coordinates which are estimated during navigation. Then, by using this developed coordinate system, absolute positions of mobile UWB sensors, referred to as tags, are calculated. For two-dimensional absolute positioning at least three anchors, and for three-dimensional positioning at least four anchors are needed. Relative positioning, on the other hand, relies only on the pairwise distance estimates between UWB sensors to define their positions with respect to an arbitrary internal coordinate system. Relative positioning does not require any prior position information or an external infrastructure such as GNSS signals, landmarks or beacons. Finding the positions of UWB sensors relative to each other is considered as an essential need in many applications which require autonomy and cooperation [39].

2.2. Integration concept for the chosen sensors

In UDOKS project, a foot-mounted IMU, aiding sensors and UWB ranging sensors will be integrated to develop a PNS. A prospective concept for the sensor integration is illustrated in Figure 1.

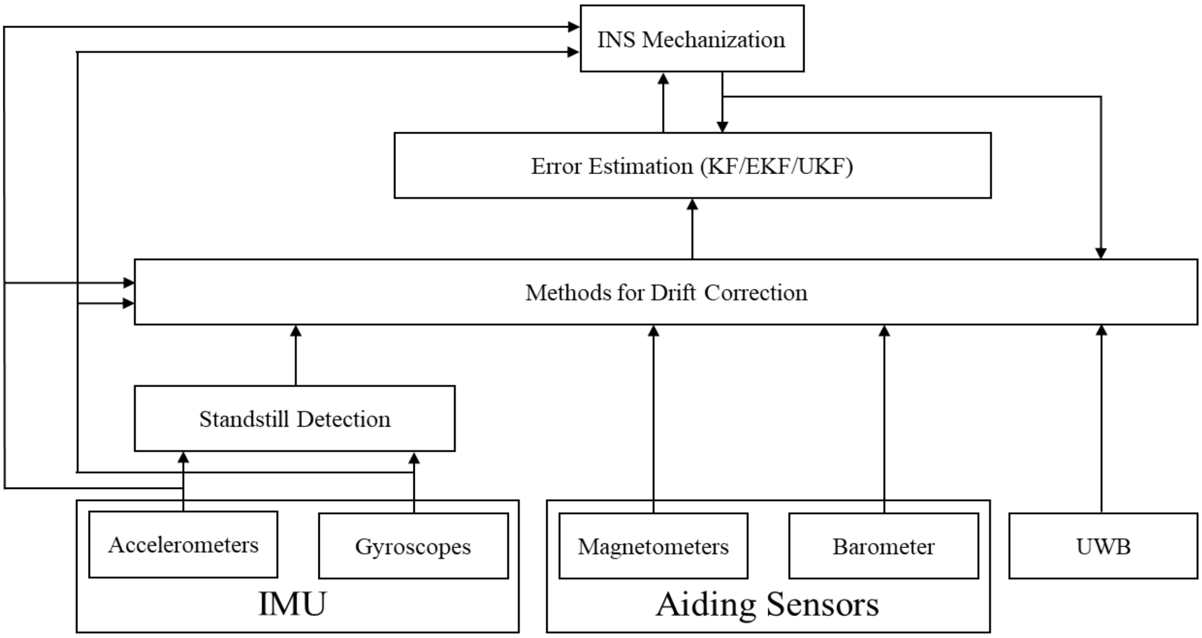

Figure 1: A prospective concept for the sensor integration of the PNS being developed in UDOKS project.

The basic idea of the integration concept is to use a Kalman-based filter (i.e., linear-KF, extended-EKF or unscented-UKF) to estimate the error states related to INS mechanization. The Kalman-based filter is updated with pseudo-measurements coming from drift correction methods and the updated error estimates are applied into INS mechanization. The inclusion of the drift correction methods in Figure 1 will be such comprehensive that it enables the Kalman-based filter to estimate the errors of all navigation states (i.e., ZUPT will provide velocity-, roll- and pitch-correcting measurements, magnetometers will provide heading-correcting measurements, barometer will provide altitude-correcting measurements, and UWB will provide position-correcting measurements).

3. Simulation environment being implemented

In parallel with the PNS development efforts described in previous section, a simulation environment is also being implemented as a part of UDOKS project. We strive to implement a simulation environment to evaluate and compare several pedestrian navigation algorithms by considering different usage scenarios and error levels of integrated sensors. To achieve this goal, the simulation environment which is being implemented should have an open and modular architecture with the capability of inserting and integrating appropriate navigation algorithms and complementary sensor technologies.

A prospective architecture for the simulation environment is illustrated in Figure 2. The simulation environment generates a trajectory in navigation frame according to the usage scenario. The generated navigation signals are then transformed into ideal sensor signals in pedestrian's body frame. Different types of sensor errors with deterministic and stochastic models are injected into the ideal signals concerning the qualities of the sensors to be integrated. The heterogeneity of the data coming from different sensor technologies is being dealt with suitable integration and data fusion techniques. Simulation environment allows the user to choose different sensor combinations which are compatible with the usage scenario. The prospective architecture of the simulation environment naturally includes the sensor combination of the PNS being developed in UDOKS project. Additionally, it includes the sensor technologies such as Wi-Fi, BLE, ultrasound [40], and GNSS (even if UDOKS project aims to develop a PNS for GNSS-denied environments, the simulation environment comprises GNSS integration assuming that for some usage scenarios GNSS is available and trusted). Thanks to the open and modular architecture of the simulation environment, along with the sensor technologies previously mentioned, the designer will have an ability to integrate other alternative technologies agreeable with the usage scenario.

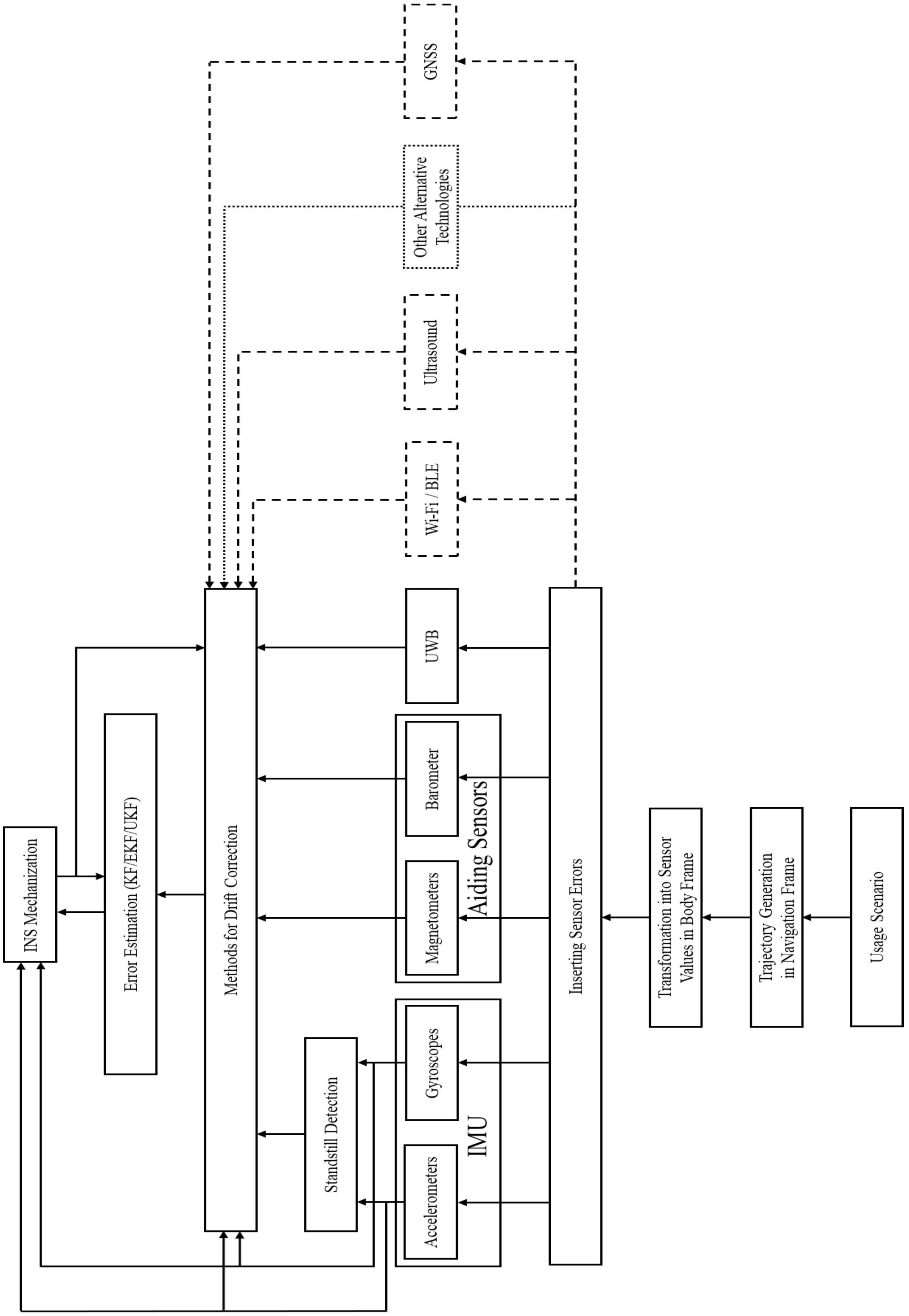

Figure 2: A prospective architecture for the simulation environment being implemented in UDOKS project.

4. Preliminary performance results

Preliminary performance results of the pure inertial sensors-based PNS developed as a single navigation system are given in this section. The developed PNS consists of only a STIM300 IMU [41] as a sensor module attached to the foot as shown in Figure 3.

Figure 3: STIM300 attached to the foot via shoe's laces.

The test was conducted in an indoor environment on a rectangular path 105 meters long. Walking the path in clockwise direction took 90 seconds. All gyroscope and accelerometer data were logged and processed afterwards using MATLAB. The conducted walking began and ended at the same point of the path. Standstill detection was carried out by utilizing the Stance Hypothesis Optimal Estimation (SHOE) detector [42] and high detection accuracies were generally obtained. ZUPT was used for drift correction and the errors on the navigation parameters were estimated by an Extended Kalman Filter (EKF).

Figure 4 shows the estimated position outputs of the PNS being developed in UDOKS project. As a preliminary performance index, the difference between the initial (the origin) and final estimated positions with respect to total distance walked is calculated. The distance between the starting point and final estimated position is 0.35 meter. Thus, the positioning error is 0.33% of the distance walked.

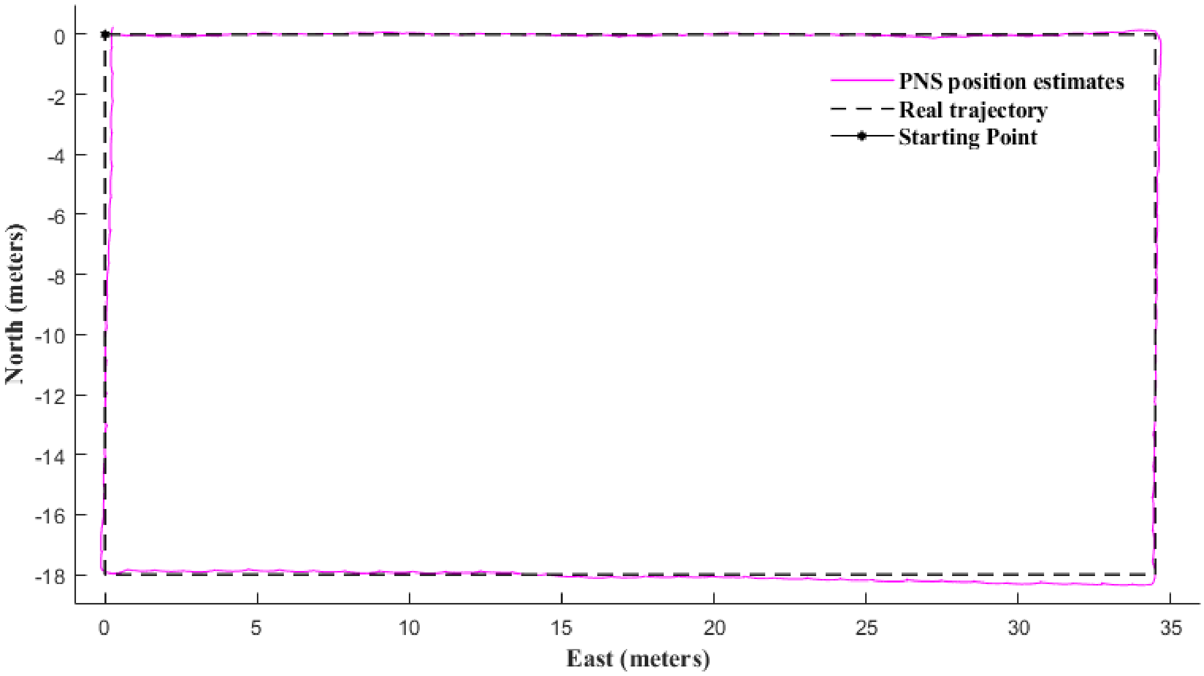

Figure 4: Preliminary indoor performance evaluation of the pure inertial sensors-based PNS developed in UDOKS project.

5. Conclusions

Developing accurate and robust navigation systems for pedestrians in GNSS-denied environments is a big challenge that has been attracting huge attention from the research, development, and scientific communities in recent years. UDOKS, ASELSAN's ongoing self-funded research project, aims at developing a PNS integrating inertial sensors, UWB ranging sensors, and aiding sensors such as magnetometers and a barometer. Traditional and proven navigation algorithms such as INS mechanization and error state estimation via Kalman-based filters will be utilized by the PNS being developed in UDOKS project. Moreover, some novel approaches, relatively newer and well-functioning methods will also be utilized to detect the standstill periods of foot motion and to bound the integration drifts in the navigation solution. Especially, assisting the inertial and aiding sensors-based PNS with UWB relative positioning solutions in a cooperative navigation concept will be one of the primary purposes of UDOKS project studies.

In addition to the PNS development efforts, a simulation environment with an open and modular architecture is also being implemented in UDOKS project. The simulation environment is expected to be a tool enabling the designer to test and evaluate new approaches and different sensor combinations during earlier phases of the PNS developments in the future.

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