DOI (by program committee)

NIKE BLUETRACK: Blue Force Tracking in Underground Structures

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In this article we present a blue force tracking system for operators in underground structures. By fusing inertial data sensed by an Inertial Measurement Unit (IMU) with distance information from Ultra-Wideband (UWB) and map information from a 3D model, a robust tracking system is introduced. Since the needed infrastructure and map model cannot be assumed available, tools are developed to provide the necessary information in near real-time. Our tests in a tunnel at Zentrum am Berg (ZaB) showed that the developed system provides robust localization information.

Key Words: blue force tracking, indoor localization, UWB, foot-mounted IMU, tunnel model

1. Introduction

Complex subsurface scenarios as they will likely arise in urban operations pose a major challenge to armed forces. The simultaneous occurrence of armed opponents, toxic gas and smoke or water ingress *(Hofer et al. (2020))*, together with the potential complexity of the subsurface structures (road and rail tunnels, subways, underground parking spaces, canalisation etc. *(Hofer et al. (2019))* requires an optimization of military tactics, techniques, and procedures to foster mission accomplishment. One supporting element is the capability of generating an accurate situational picture, i.e., localizing one's own forces to enable navigation in contorted tunnel systems with bad lighting or smoke and to avoid blue-on-blue situations. Such a blue force tracking system that can localize the own forces in tunnels and visualizing the situational in a virtual reality, is developed in the NIKE BLUETRACK project.

The major challenge of such an underground tracking system is the absence of satellite signals, rendering GNSS-based positioning as the de-facto localization standard unusable. To achieve the goal of GNSS-free real-time tracking of an operator in the tunnel, three levels of architecture are proposed. As shown in Figure 1, the operator is carrying out and placing UWB anchors during the mission and therefore setting up a custom UWB network. Each operator itself is equipped with a main processing unit (MPU), an UWB tag and two micro-electro-mechanical system (MEMS) IMUs. Outside of the tunnel a stand-alone Server is running. Data is transferred in several directions between these systems. UWB and processed IMU data are read by the MPU and combined in a particle filter. The initial position for the filter is provided by a pre-installed UWB network outside the tunnel. The output positions and UWB distances are then sent to the server and estimated anchor coordinates are returned. Filtered positions of all operators are also visualized centrally on the virtual reality environment "Subsurface Operation Mission Tool" (SOMT). Additionally, maps are generated by the Fast Tunnel Modelling Tool (FTMT). These are broadcast to the MPUs to improve the filter solution. As MPU a Raspberry Pi Model 4B with at least 4 GB RAM is chosen. The software development is based on Python 3.9 using the Robot Operating System framework for sensor communication.

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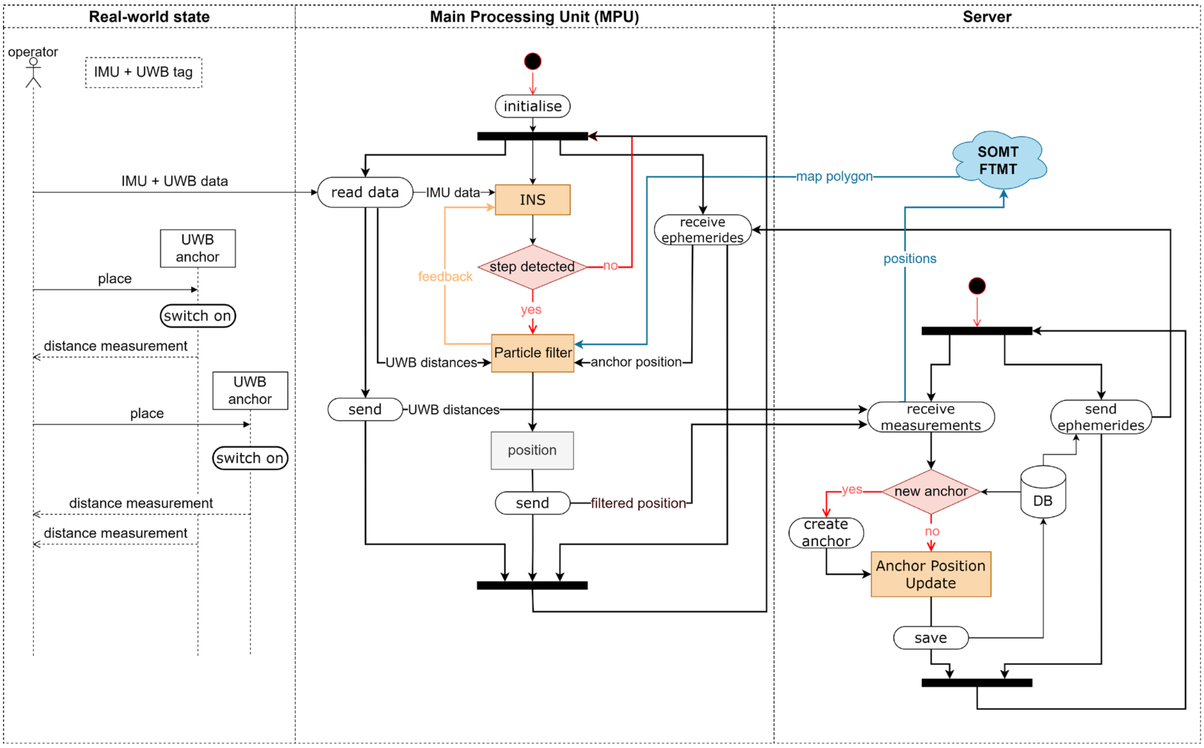


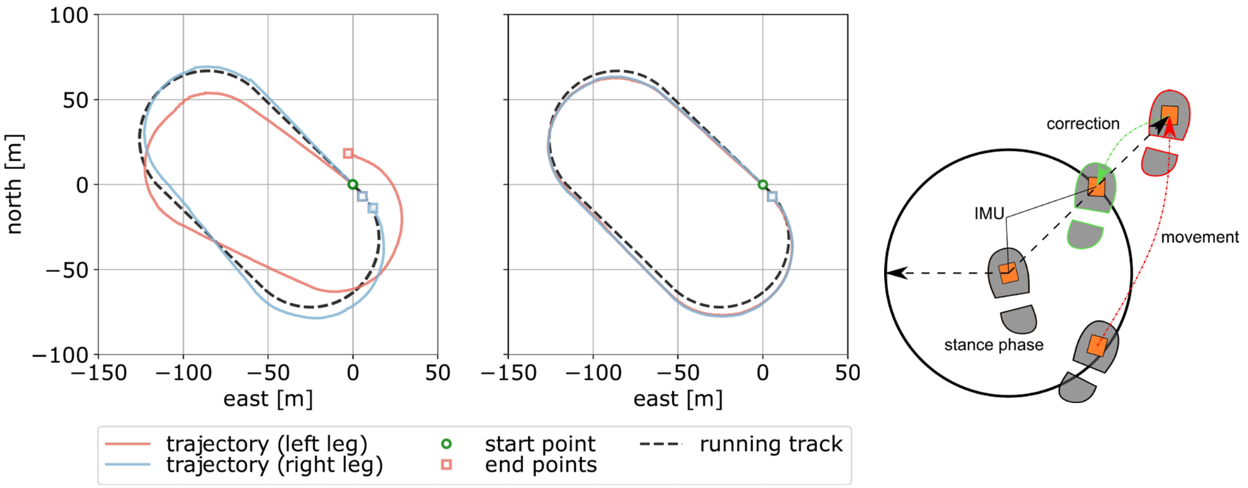
Figure 1: System architecture NIKE BLUETRACK

2. Dual Foot-Mounted Inertial Navigation System

Based on current accelerations and angular rates, sensed by a MEMS IMU, relative changes in velocity, position and attitude can be derived. Starting from a known position and orientation, the current position and orientation are determined by integrating twice over the accelerations and once over the angular measurements. The technical term for the system applied here is "Inertial Navigation System" (INS). The major advantage of an INS is that it is a self-contained device and that it can handle forward/backward/lateral movements in contrast to a classical dead reckoning system. However, due to several sensor errors, like biases, the solution tends to drift over the time (already after some seconds).

An INS without any additional external information, especially one equipped with low-cost IMUs, does not deliver reliable positioning information over larger periods of time. A possible solution to mitigate the drift behaviour is the introduction of so-called zero-velocity updates (ZUPTs) *(Noureldin (2013))*. In our case, the IMUs are mounted on the foot. During stance phases, the INS should output zero speed. Due to the sensor errors, this is typically not the case. By telling the system that the actual velocity is zero, the drift can be partly corrected. An essential impact of the performance of a ZUPT is the reliable detection of those stance phases. In our study, we utilized machine learning methodologies in form of a recurrent neural network to detect zero-velocity events for varying motion types (walking and running at different speeds) *(Mascher et al. (2022))*.

However, a ZUPT reduces the position and velocity errors and has no observational effect on the heading angle *(Li et al. (2021))*. The heading describes the direction in which the operator is pointing. By introducing a spatial constraint between the left and right IMU (Figure 2 (b)), the heading drift can be reduced. If the distance between the two legs is greater than a pre-defined maximal possible step length, a correction is applied *(Prateek et al. (2013))*. Figure 2 (a) shows an example track at the athletics track at Universitätssportzentrum Rosenhain (Graz/Austria). The pedestrian subject performed a whole lap (~ 400 m) and randomly changed to faster and slower gaits. In the left panel, the individual INS trajectories are displayed. As it can be seen, they drift apart over time. By introducing the constraint that both legs cannot be further apart than the maximal possible step length (right panel), the solution can be significantly improved.



(a) (b)

Figure 2: (a) INS trajectories. The left and right panels show the individual and the fused solution of the foot-mounted INS, respectively. (b) Utilizing a spatial constraint between left and right foot to mitigate the systematic heading drift (Mascher et al. (2022))

Major advances of ZUPTs and the fusion of two IMUs are their simplicity and inexpensiveness to the system. Nevertheless, the sensor drift cannot be fully eliminated by the described methods. Thus, the integration of the INS with additional information, such as map information, or absolute positioning techniques is necessary to provide reliable navigation information over a longer period of time. The initial heading is determined by a magnetometer outside the tunnel.

3. Fast Tunnel Modelling

The Fast Tunnel Modelling Tool (FTMT) provides georeferenced 3D models of subsurface structures *(Hofer et al. (2021))*, such as tunnels or subways in near real-time. For this project, FTMT delivers the tunnel axis and a polygon that describes the areas in which operators can be present. Based on the given information of the FTMT, it is ensured that the operator is inside, e.g., a tunnel.

4. Ultra-wideband

Ultra-wideband is a communication signal, which recently gained popularity as signal of opportunity in indoor localization. Distinctive for UWB is the bandwidth above 500 MHz or at least 20 % of the carrier frequency *(Subedi et al. (2020))*. This results in less interference compared to Wi-Fi and reduces vulnerability to attacks *(Simedroni et al. (2020))*. By measuring the reception time of an UWB pulse at the tag and an anchor, the time of flight can be calculated. With the speed of light, the final distance between the two UWB sensors is obtained. If the position of the anchors is known, a position can be approximated with minimum three ranges. However, less ranges can still narrow down the possible location of an operator. The achievable accuracy with UWB is below 1 m. Due to imperfect placement of the anchors in a tunnel and errors due to reflections of the signal the performance decreases in practice *(Watzko (2022))*. To improve this coarse estimation, additional information is necessary. Therefore, IMU data and map information are fused with the UWB ranges in a particle filter. The recorded UWB ranges of a measurement campaign in a street tunnel can be found in Figure 3. Two anchors (43B9 and 000B) were passed multiple times while walking two laps in the tunnel. It is visible that UWB can reach a range up to 140 m. However, measurements are noisier and more influenced by multipath towards the maximum capability. Outliers can also be found on the right hand plot, which provides shorter ranges. This is due to metallic surfaces, such as parked vehicles and metallic signs close to the anchors. One also has to keep in mind that the chosen UWB system can only measure to four anchors at a time. The choice of anchors and switching between them is performed automatically.

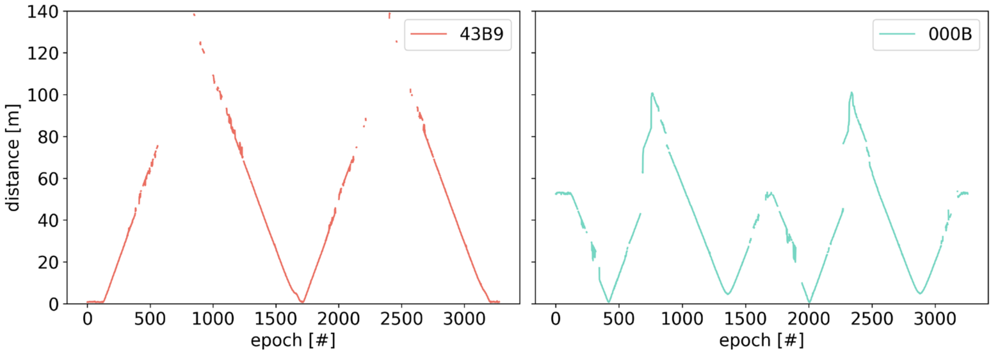


Figure 3: UWB distances to two anchors in practice

5. Integration (Particle filter)

Integration of multiple sensor systems is a key point in order to achieve reliable, accurate and continuous results. Due to redundancy, faulty measurements can be detected, and individual disadvantages of sensors compensated. The pros and cons for the deployed sensors can be found in Table 1.

Table 1: Characteristics of used sensor systems

System	advantages	disadvantages
INS	no external influence high data rate	no absolute information drift of position and height
UWB	absolute position epochs independent	prone to external disturbance external infrastructure needed
Map	absolute information	dependent on data quality

In case of the proposed filter system the UWB sensor is used to minimize the drift of the INS, while simultaneously the noisy trajectory and outliers of the UWB measurements are mitigated by the INS. The map information on top should further reduce the drift and low accuracy in the height component of both UWB and INS. An overview is given in Figure 4.

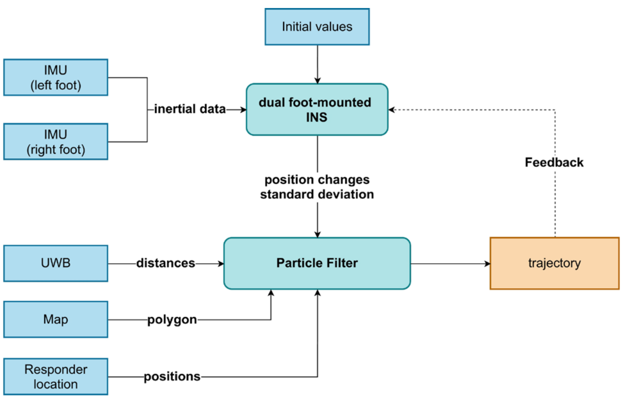


Figure 4: Filter architecture (Mascher et al. (2022)).

The main component of the system is the particle filter. This Bayesian filter is well suited for fusing position information with maps and can also handle non-Gaussian measurements as expected from UWB *(Hafner (2015))*. Goal of the filter is the best estimation of a state (position and direction), which describes the movement of the operator, based on given measurements. In case of the particle filter, the state is represented by individual particles. These particles can move in space and are assigned weights based on the measurements. After an initialization with UWB ranges in an outdoor environment, the particles are propagated forward with position and attitude changes of the INS. Then each particle is given a weight based on the UWB measurements. In a next step, particles are weighted based on their height in comparison to the map height. Particles, which lie outside the tunnel borders are eliminated. The final state containing position and heading is estimated by computing a weighted average of all particles.

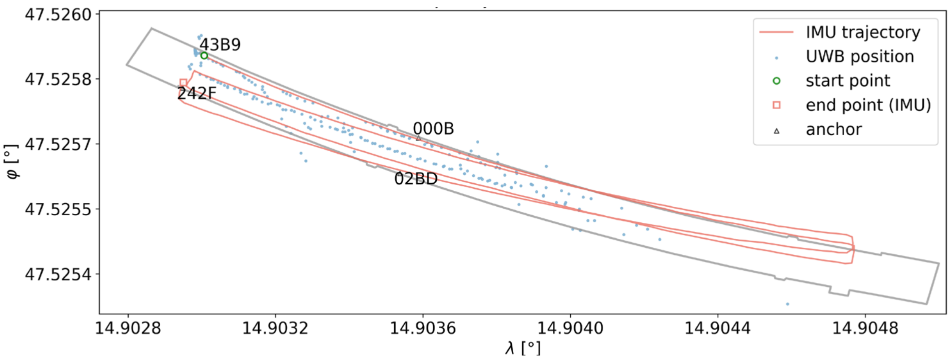


Figure 5: IMU trajectory and UWB positions for a selected route in the street tunnel north (STN)

Figure 5 shows the individual inputs of the filter for an exemplary route through the street tunnel north at the Zentrum am Berg (ZaB). In the IMU trajectory a slight drift is visible. It accumulates to an error of approximately 10 m. For comparison, UWB positions are shown. Since three ranges are needed for a position, in the eastern part of the tunnel no positions are plotted. According to Figure 3, there are still single ranges accessible in this region.

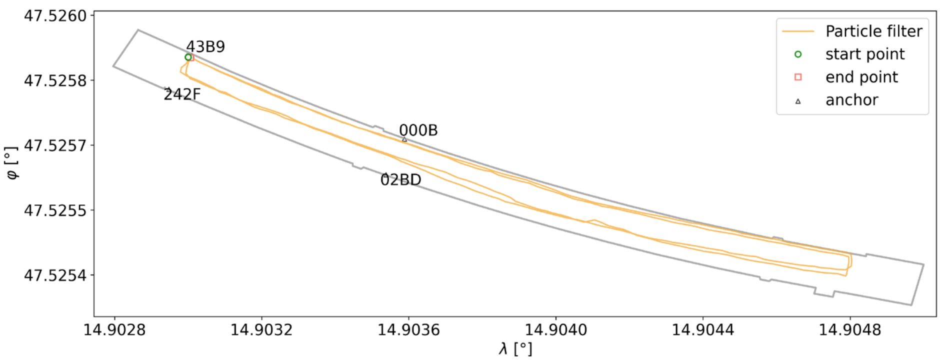


Figure 6: Particle filter trajectory for a selected route in the street tunnel north (STN)

Figure 6 presents the filtered solution. Due to the map information the trajectory is kept inside the tunnel. In the part with less UWB measurements the solution mainly follows the INS trajectory and, therefore, starts to drift. With reinstating of the UWB ranges, the trajectory finds back on track and closes the loop. Overall, the solution is close to the real track, which followed the northern wall and the centerline of the tunnel.

6. Setting up the UWB Infrastructure

UWB is an infrastructure-dependent localization technique. This means that UWB anchors with known coordinates have to be existing in the operating environment to enable absolute positioning. It is clear however, that there won't be an existing UWB infrastructure in relevant operating environments. Therefore, a procedure and technique for creating the infrastructure during the mission has been developed. The procedure is based on the assumption that it should always be possible to set up a small UWB network outside of the dangerous zones. This first network enables UWB-based positioning at the starting position of an operation. During the first advance into the tunnel the positioning will rely on the IMUs. During this phase anchors are placed by the operator while they move through the tunnel. A centralized anchor mapping algorithm *(Mascher et al. 2022)* has been developed to determine the anchor coordinates using UWB measurements and position information from the operators moving through the tunnel. The estimate of the anchor coordinates is sequentially improved and made available to the particle filter running on the operator's hardware.

7. Conclusion/Outlook

The more intricate an underground structure is, the more critical it is to know the position of the own forces. Reliable position information offers the command post a possibility of a fast and correct representation of the mission - making the decision process easier and more efficient. Thus, the authors present a real-time blue force tracking system in underground structures based on two foot-mounted IMUs, UWB and map information from FTMT. In this case, we assumed that a pre-installed infrastructure is present. Nevertheless, our set-up shows that the navigation system provides robust localization information on operators and that the INS drift is small enough to place new anchors in the infrastructure-free zone.
Our future work will focus on the anchor deployment in more detail. In a fully developed stage, NIKE BLUETRACK will make a huge contribution to the NIKE research and development program.

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