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# Emerging Wireless Technologies for Reliable Indoor Navigation in Industrial Environments

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**ABSTRACT**

Reliable positioning systems are key drivers for location-based services in smart logistics and internet of things (IoT) applications amid the era of Industry 4.0. They are the foundation blocks upon which navigation applications are built for all client segments ranging from public individuals to industrial firms. This research article investigates the existing wireless radio technologies from a low-cost opportunistic perspective to provide precise positioning for dense indoor scenarios. In indoor scenarios, it is a rule of thumb that modern humans spend more than 90% of their time inside buildings, and yet, only a few indoor positioning systems are: less available, more expensive, more disruptable, and/or less accurate. One major reason is that the current indoor positioning technologies are compromising the system performance with other essential metrics such as the overall cost. For instance, the most accurate (millimeter level) indoor positioning technology -so far- is the LASER technology, however, it is massively expensive. On the other hand, some of the existing low-cost positioning technologies for indoor venues are less accurate, besides having other performance drawbacks. One prominent solution for dense indoor situations is Ultra-wideband (UWB) technology, as it provides a positive trade-off between operational costs and system performance. UWB has recently emerged to deliver precise indoor positioning solutions within a centimeter level of accuracy while being a reliable low-cost technology. It is foreseen that UWB will be embedded inside many smartphone models in the near future, some phone manufacturers have already started adopting UWB-chips in 2019 such as Apple and Samsung. Moreover, the FiRa consortium was established by giant founding companies such as Cisco, Google, Samsung, BOSCH, Apple, and Qualcomm, to promote UWB as an indoor positioning technology. Quoting from the FiRa website as follows "UWB is the most effective available technology for delivering accurate ranging and positioning in challenging real-world environments, allowing devices to add real-time spatial context and enabling new user experiences". Previously in 2021, we conducted a thorough review study on UWB, in which we concluded that UWB is an industrial-friendly technology that can provide higher rates of accuracy while maintaining continuous service levels at low costs. In a well-established industrial laboratory in the Ostrobothnia region, Technobothnia, we performed technical experiments to deliver precise UWB positioning for individuals and mobile assets such as autonomous robots. Aided by sensitive inertial motion units (IMUs), the results showed that the UWB precision positioning in a dense challenging environment (i.e. Technobothnia) has been achieved to mean absolute error of **3.7 centimeters** accuracy, and a Wi-Fi positioning accuracy of **4.5 meters**. Our future objective is to further improve the positioning accuracy and reliability to facilitate autonomous operations by mobile robots in the lab. Later, our system will be made open to the public use e.g. for students, visitors, and staff as beneficiaries. Besides UWB technology, there are some additional opportunistic methods that are less accurate (ultra-meter(s) accuracy) however, can be assisted with other multisensor technologies to achieve reliable positioning solutions. The methods that are being investigated are Bluetooth low energy (BLE) and Wi-Fi positioning. The idea is based on the signal-of-opportunity (SOP) paradigm, in which the positioning solution is rendered by measuring one of the radio signal properties, that is, the received signal strength indicator (RSSI). By integrating with IMU sensors, the multisensor combinations BLE/IMU and WiFi/IMU can result in meter-level accuracy, which can be regarded as reliable positioning for certain indoor applications. Moreover, the use of both techniques is foreseen to be sufficient for laboratory mobile activities, as their typical multisensor positioning accuracy can range between 1.5 to 3 meters. The main objective of our proposed method is to refine the achieved positioning accuracy from the multisensor system using a series of algorithmic remedies. First, the positioning solutions are filtered via Bayesian filters to remove the noisy effects and DC offsets. Then, the multisensor scheme is selected as either loose or tight coupling to integrate the IMU readings with the radio-based RSSI estimations and overcome the non-line-of-sight (NLOS) effects. Afterward, the fused solution is treated with recursive Kalman smoothers to further refine the positioning traces, and remove sharpness and stationary effects. The final (optional) step is to apply some machine learning algorithms to adapt navigation routes to the real surroundings based on the collected training data. As a ground truth for all systems and also as training data, an accurate mobile robot is used to bear all sensors together during the experiments. The robot is equipped with LiDARs, ultrasounds, radars, and LASERs that can achieve millimeter accuracy, hence, the data recorded by its sensors are treated as ground truth as well as training data. We also developed an embedded system that synchronizes all data pools together coming from different sensors (UWB – WiFi – BLE – IMU) in the same time frame. In summary, this article studies the indoor navigation opportunities created by existing radio positioning technologies that are tailored for industrial use cases, using multisensor fusion methods for both precise and fingerprinting techniques. A special focus was given to UWB technology as it will be abundant in the near future by embedding smartphones, home appliances, and body wearables with commercial-grade UWB chips, which was already started in 2019. Additionally, we focused on the Wi-Fi based IPS for mobile assets (e.g. robots and humans) that are not necessarily requiring to have precise positioning, few meters of accuracy are becoming sufficient. The existing infrastructure in Technobothnia is currently being customized to embed BLE hardware into the designed IPS, however, the software part has been already implemented. Those RSSI-based indoor positioning methods are becoming trending in large indoor venues (e.g. airports, malls, and train stations) as well as being adopted by major positioning corporations. Consequently, we studied some algorithmic optimization techniques to transform both fingerprinting methods into more accurate reliable techniques. As future research, our proposed methods can be further adapted to be applied for real-time applications, and ensuring that all technologies (including BLE) are functional and up running.

*Keywords: Radio technologies, indoor positioning, dense environments, mobile robots, industrial applications.*

## I. INTRODUCTION

Indoor positioning systems (IPSs) are crucial for Industry 4.0 and Internet of Things (IoT) applications. Several indoor location-based services are dependent on IPSs such in: asset tracking, smart manufacturing and logistics, and so forth [1, 2]. IPSs exist with numerous advantages, yet they face many challenges from multiple sources. In principle, an IPS is assessed for reliability by achieving acceptable levels of performance in the following metrics: accuracy, availability, continuity, and integrity [3]. For this reason, a reliable IPS incur significant costs to compromise all metrics down to sufficient degrees, especially when the application has a high level of sensitivity and low tolerance to errors e.g. healthcare, military, and sophisticated applications. It is abundant that wireless-based IPSs may suffer from signal discontinuities (also known as non-line-of-sight (NLOS)) as the wireless electromagnetic waves are highly prone to channel impairments while propagating in free air, besides the blockage and signal denial in some dense environments.

In addition to the conclusive results from our previous studies found in [2], new researches also support the feasibility of designing a reliable low-cost IPS by integrating multiple technologies together to combat the effect of NLOS situations [4]. Thus, a reliable IPS is not necessarily dependent on a single technology, rather, multiple technologies could be fused together (i.e. multisensor) to realize the desired performance and get better positioning estimations. Multisensor fusion is the integration of two or more technologies using computational paradigms that are implemented by fusion algorithms such that the combined (fused) information is enhanced [5]. Sensors are by-default prone to systematic errors and biases, consequently, multisensor fusion techniques could play an important role in mitigation of errors to the possible minimal.

To this aim, we implemented the essential elements of our proposed IPS inside a real dense environment located on the campus of our research institute (University of Vaasa, Finland), called Technobothnia laboratory. It is a modern laboratory that serves many universities and corporations in the region, as shown in Figure 1. Technobothnia hosts significant visiting traffic owing to the laboratories within, which support various kinds of technical sciences. Consequently, an indoor positioning system will be very beneficial to the movable assets (i.e. humans and robots) who are operating inside the lab.

**Figure 1:** An indoor aerial view of Technobothnia laboratory, situated in Vaasa, Finland.

Nevertheless, the available resources for positioning inside the lab tend to low-cost IPSs that are based on wireless technologies e.g. ultra wide-band (UWB), Wi-Fi, Bluetooth low energy (BLE). An UWB system and an inertial measurement unit (IMU) are selected as the elements of the precise IPS in Technobothnia, with UWB as the primary technology, and IMU as the assisting sensor fusion unit. Then, Wi-Fi and BLE in addition to an IMU unit were considered for the less accurate (fingerprinting) IPSs that shall track assets within a couple of meters as accuracy. The foundation of UWB and Wi-Fi were implemented successfully to Technobothnia while the BLE hardware infrastructure is still under development to the date of writing those lines. That is, UWB to track assets (e.g. robots and/or humans) within sub-meter level of accuracy, while Wi-Fi to position assets within ultra-meter level of accuracy (i.e. suitable for humans not robots).

The rest of article is organized as follows: Section II states the main approach of this research in addition to the building blocks of the intended IPS systems from software and hardware perspectives. Section III highlights the realized technical actions to obtain the planned IPS e.g. methodology, devices configurations, and the overall setup of the environment. Section IV discusses the output results and provides some technical interpretations, evaluations, and comments regarding the applied methodologies. The article finalizes with a "Conclusion" section to summarize the results and the achieved IPS performance.

## II. DESIGN OF THE FUSION-BASED IPSS

In this section, we describe the whole design aspects of building both UWB and Wi-Fi indoor positioning systems. As described in the introduction, it is the main objective in this research to build two dedicated IPSs that ensure the most possible degree of precision positioning for movable assets (robots using UWB, and humans using Wi-Fi) inside our industrial laboratory of Technobothnia, Finland.

### 1. Outlines

The dense challenging environment in Technobothnia required a multisensor fusion technique to achieve better accuracy and also keep the overall budget (e.g. costs and time) under the allocated limits for building those IPSs. A low-cost system can be built from a single precise wireless technology such as UWB then fused with an assisting technology [2]. Hence, an IMU could be employed to correct the biased, missing, and null values caused by NLOS conditions especially in dense environments.

To this aim, a loosely-coupled UWB/IMU integrated scheme was implemented as a precise IPS for mobile robots in the selected venue, and another loosely-coupled scheme Wi-Fi/IMU for localizing humans. A floor plan of the experiment area at Technobothnia laboratory is illustrated in Figure 2.

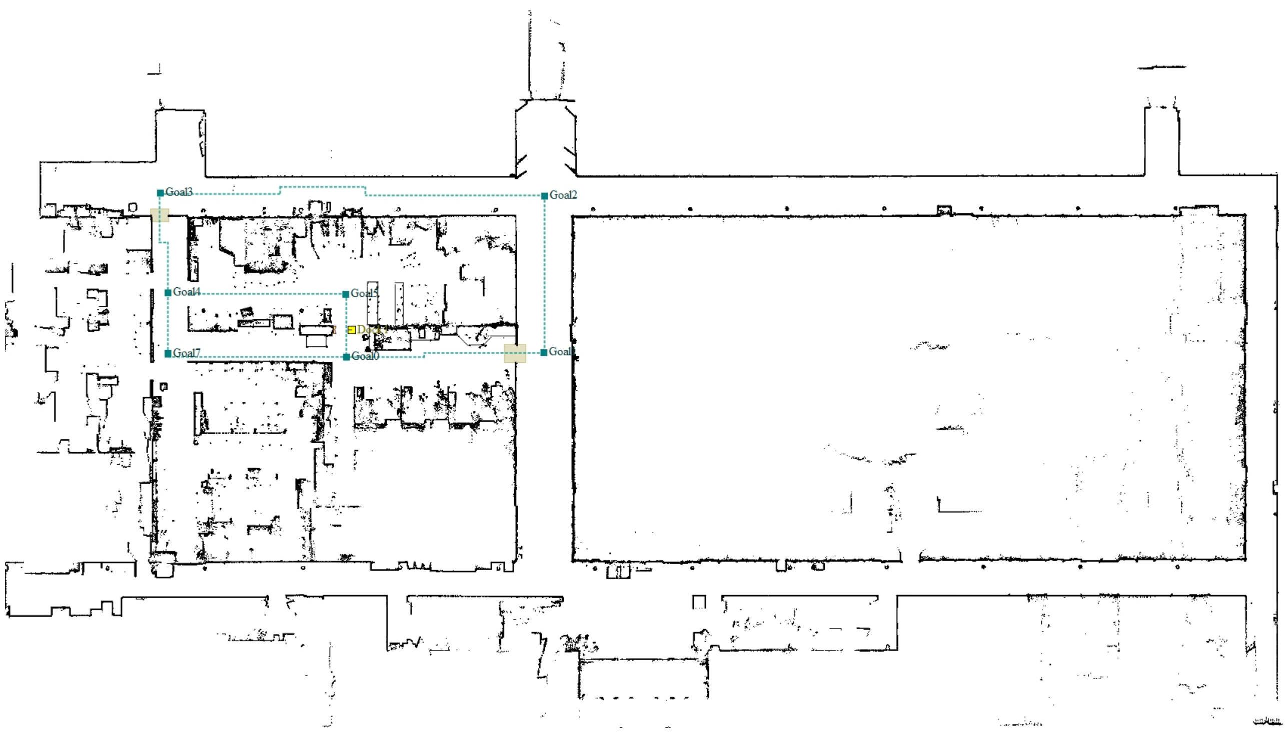


**Figure 2:** Snapshot from the robot's internal software system showing the floor plan of the whole laboratory building (Technobothnia) after calibrating the map several times. The dense area in the top left-hand corner is our lab area where most technical operations take place.

### 2. Positioning devices

The testing setup involved patrolling the environment by an autonomous robot whose accuracy is millimeter level, thus can be considered as a source of ground truth data. All other sensors such as: UWB, IMU, and received signal strength indicator (RSSI) scanners (for Wi-Fi and BLE) were mounted on the patrolling robot to get the same route information as the robot.

*a). UWB IPS*

For UWB, a Decawave laboratory kit MDEK1001 [6] was adopted to represent the UWB IPS inside our industrial laboratory environment, Technobothnia. However, for Wi-Fi IPS we had to interface with the access point devices opportunistically, meaning that we have utilized the existing infrastructure (that was developed by our institute's IT department) by recording the essential information of the distributed router access points in the area such as: MAC addresses, received signal strength indicator (RSSI), and LASER-measuring their locations to be included in our reference coordinate system (all devices were given the same unified axes and origin point).

In addition, an inertial measurement unit (IMU) sensor Xsens MTi-630 was employed to obtain the inertial data of the user (i.e. the robot) such as: orientation, rate of turn, acceleration, and magnetism. The introduction of IMU sensor provided another layer of information regarding the movement of the robot inside the dense environment. Therefore, IMU helped in accounting for the NLOS situations and inferring the missing data to improve the final positioning estimations.

Our setup for the UWB system consisted of one movable tag (the user), and six evenly distributed anchors to cover the experimental area of 28x15 squared meters evenly, an additional seventh anchor was added to clear the ambiguities of that dense area. The default settings of the Decawave kit are factory-programmed to provide raw distance measurements between the moving tag and a maximum of four anchors (constrains from Decawave) based on the time of arrival (ToA) two-way ranging (TWR) technique, in addition to providing the EKF estimation of the tag position [6].

Both UWB and IMU sensors were placed onboard an autonomous mobile robot developed by OMRON. The robot has several positioning sensors of LASERs, ultrasound, RADARs, IMU, and LiDARs which yield a millimeter accuracy therefore it acted as the reference ground truth to both UWB/IMU and Wi-Fi/IMU fusion systems.

*b). Wi-Fi IPS*

As mentioned earlier that the Wi-Fi IPS was approached opportunistically. There were six router access points that cover the operation area, we referred to them as: $R_0, R_1, R_2, R_3, R_4, R_5$. We decided to build mathematical models for every router solely, therefore, several RSSI measurements were taken at reference distance of 1m, 3m, 5m, and 10m, those distances were measured using a LASER- ranger. We assumed logarithmic path-loss models to find the relation between the RSSI and the distances from the router. The used formula is found in Equation 1, as follows [7]:

$$B_k = B_0 + 10\alpha log(d_k) + X_\sigma \tag{1}$$

Where $B_k$ is the measured RSSI at a given $k$ time instant, $B_0$ is the measured RSSI at the reference distance (one meter), $\alpha$ is the medium path loss exponent, $d_k$ is the estimated distance in meter for a given $k$ time instant, and $X_\sigma$ is a random variable with standard deviation $\sigma$ that represents a white zero-mean Gaussian noise.

The results of curve-fitting the logarithmic path-loss models provided the values of the characteristic variables ($\alpha$, $B_0$) of every router, as shown in Figure 3.

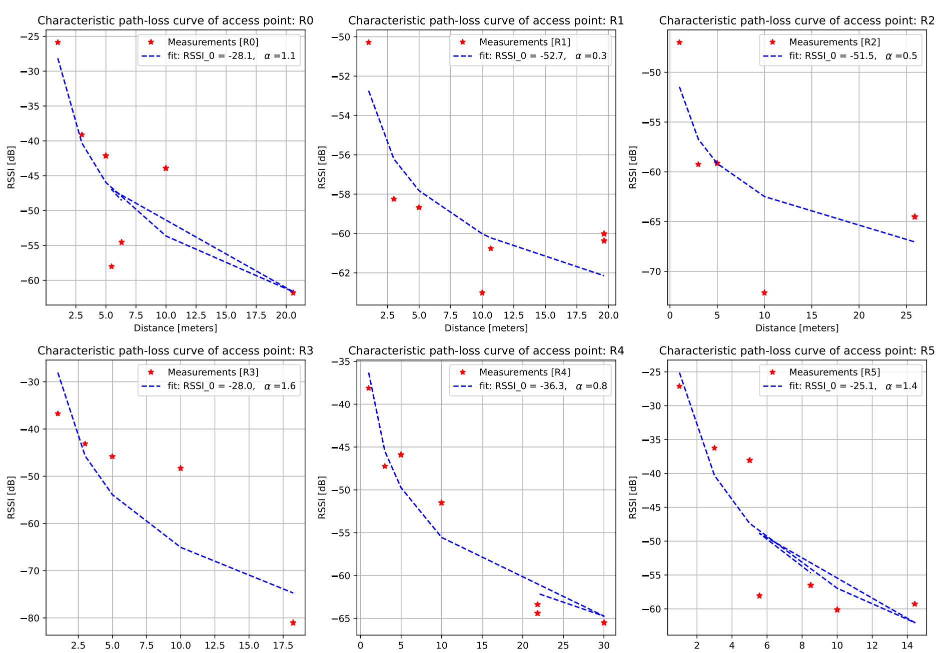


**Figure 3:** Curve-fitted characteristic path-loss curves of all access points [R0 – R5].

From the curves in Figure 3, it is clear that some routers (especially $R_0, R_4, R_5$) are having constant RSSI values over several displacements, which means that the RSSI does not change over distance in some cases. This is an important concern in this method, and it is a natural result to being offered some shallow information about the access points. A better approach was to get localization-compatible router brands whose characteristic RSSI vs distance curves are following typical logarithmic relations.

## III. EXPERIMENTAL SETUP

In this section, we showcase the prepared setup from software and hardware perspectives that was used for performing robot experiments inside our laboratory.

### 1. IPS system level design

In order to test our proposed fusion-based IPS systems of UWB/IMU and Wi-Fi/IMU, we deployed a customized embedded system that holds the essential software and hardware elements to carry out the experiments in the selected environment.

The hardware part consists of a distributed set of seven UWB anchors (Decawave) with fixed positions around the coverage area, the IMU sensor (XSENS) mounted on the mobile robot, the laptop recorder was equipped with UWB data logger and RSSI scanner, and the robot itself (OMRON).

The software part was developed using Python and JavaScript to record and communicate real-time data from-to a storage web server. We built the system to bear multiple positioning sensors in the same venue e.g.: robots sensors, UWB anchors, Wi-Fi access points, Bluetooth (future use), and inertial sensors. All sensor points are attached to their corresponding software scanner(s) that records the desired data observables using the appropriate unit settings. Then, all scanners pass the information to the NodeRed server via web sockets, to be stored in a local storage that is interfaced by our team (i.e. the user).

It is worth noting that the BLE software scanner is already developed and up-running but at the moment it has been reserved for future use, as the hardware infrastructure is currently under development. Therefore, the focus of this article will be centered around UWB/IMU and Wi-Fi/IMU fusions.

### 2. Calibration and configuration

We calibrated the robot's sensors as well as the UWB, IMU and Wi-Fi devices. For the robot, we created a new topology map for the environment and all its furniture, barriers and structures, which was uploaded to the robot's internal storage to mark the boundaries of the experimentation area. IMU sensor was factory-calibrated already. Then for UWB, we calibrated the Decawave anchors to know its covariance error and set the physical coordinates of anchors' locations by the aid of a LASER meter ranger. Same with Wi-Fi access points, we primarily wanted to interface them from system level (by the aid of our IT department), however, we had to work with Wi-Fi access from an opportunistic approach (i.e. deal with them as electromagnetic-wave emitter devices) whose RSSI and MAC information are known. Furthermore, the origin points of all sensors were aligned into a single origin point (0, 0) explicitly marked on the laboratory floor and programmed into sensor configurations. All calibration measurements were taken and recorded several times to ensure maximum stability and accuracy, and devices were configured to 10 Hertz sample rate.

### 3. Data flow and algorithms

The flow of data was designed to pass from sensor devices to internal data storage called Node-Red via web sockets made specifically to log all sensor data in real-time. Figure 4 illustrates the journey of sensors data in the system to achieve final positioning estimations.

Having all time series data after the web socket reception, the data was fetched to undergo pre-processing and pipe-lining phases. For the Wi-Fi data, the pre-processing step was very complicated since the routers information were interleaved by our IT department for security reasons, thus we had to find out the right MAC addresses information associated with each router, which were not the same as the manufacturer's.

Afterwards, each sensor data that conclude the pre-processing step were referred to a set of additional refining algorithms. In UWB, we replaced the null values by the aid of dead reckoning (DR) algorithm, then propagate the outputs to extended Kalman filter (EKF) fusion, Rauch-Tung-Striebel (RTS) smoother, and linear regression (LR) algorithms. The same sequence applies for Wi-Fi except that the treated Wi-Fi RSSI values are primarily passed through path-loss model in order to be later consumed by a bootstrap Particle filter (PF). Then, the PF estimates the Euclidean distances between the moving user and the fixed Wi-Fi access points with known locations.

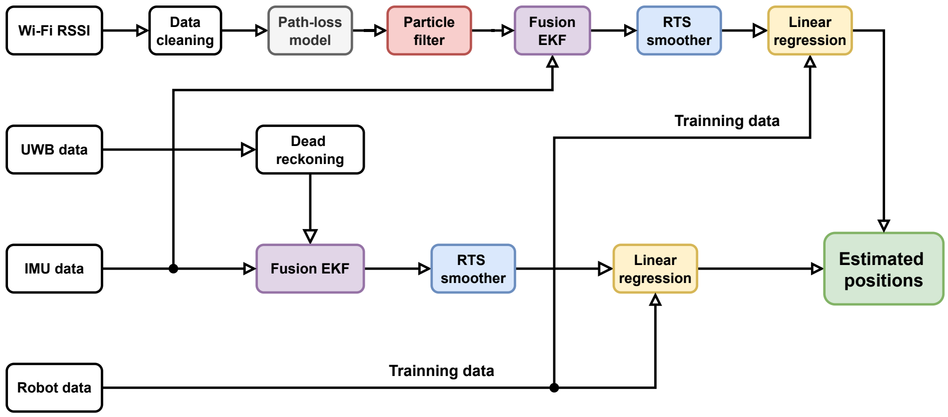


**Figure 4:** Data flow of measurements and the utilized algorithms to achieve positioning estimations.

### 4. Route design

On the robot's software controller (Mobile Runner), routes were programmed to allow the robot patrolling the coverage area in mixed situations: 1) clear LOS between the robot and the wireless devices, 2) poor LOS, 3) visibility through concrete and metal structures, and 4) with the fewest number of devices (i.e. three) visible to the robot. The locations of the first six UWB anchors were selected to provide evenly distributed coverage to the robot (e.g. rectangular shape), then a seventh anchor was inserted in the most dense space inside the environment to provide more visibility to the moving robot (UWB tag and RSSI scanners).

## IV. RESULTS AND DISCUSSION

After holding several lab experiments in Technobothnia using the described experimental setup and settings, some very promising results emerged from UWB IPS, and some other concerning results emerged from Wi-Fi.

Firstly, UWB plot results are shown in Figure 5. As seen from the figure, the performance of the latest algorithm (LR-UWB/IMU) in the UWB IPS is truly unmatched. As found from the numerical results shown in Table 1, the positioning accuracy of UWB IPS has been achieved between 3.7 – 4.5 centimeters.

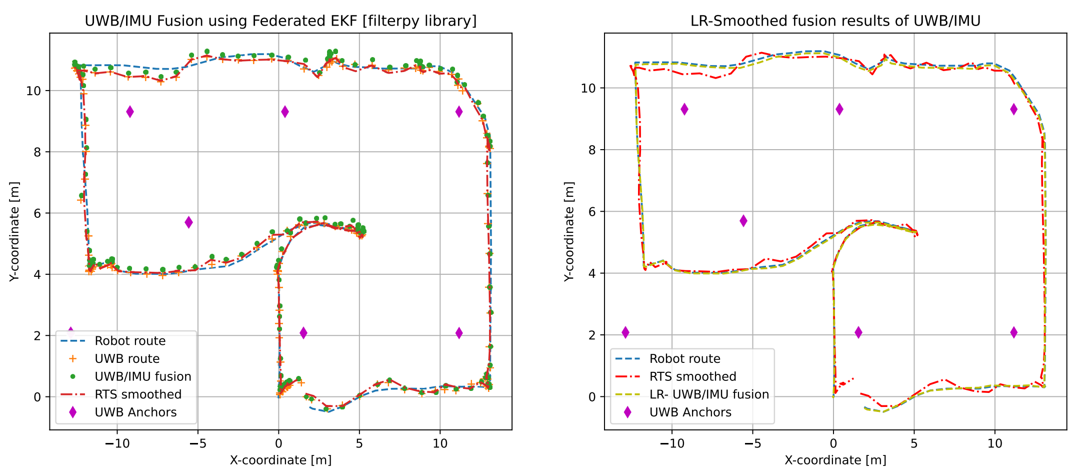


**Figure 5:** Results of UWB positioning before and after applying Linear Regression algorithm.

On the other hand, the results from Wi-Fi IPS shown in Figure 6 graphically, and Table 2 numerically were clearly erroneous, which was very much expected for various reasons. Only minor improvements occurred before applying the LR algorithm, this means that the performance of machine learning algorithms is a very prominent non-model candidate for reliable indoor positioning.

The sources of Wi-Fi IPS errors could be due to: 1) inconsistent path-loss readings that may be originated from 2) incompatible

**Table 1:** Positioning errors [in meters] of UWB IPS.

| | UWB Kalman Filter | UWB/IMU Fusion | UWB/IMU +RTS | UWB/IMU/RTS +LR |
|---|---|---|---|---|
| **MAE** | 0.170 | 0.196 | 0.169 | 0.037 |
| **RMSE** | 0.241 | 0.270 | 0.240 | 0.045 |

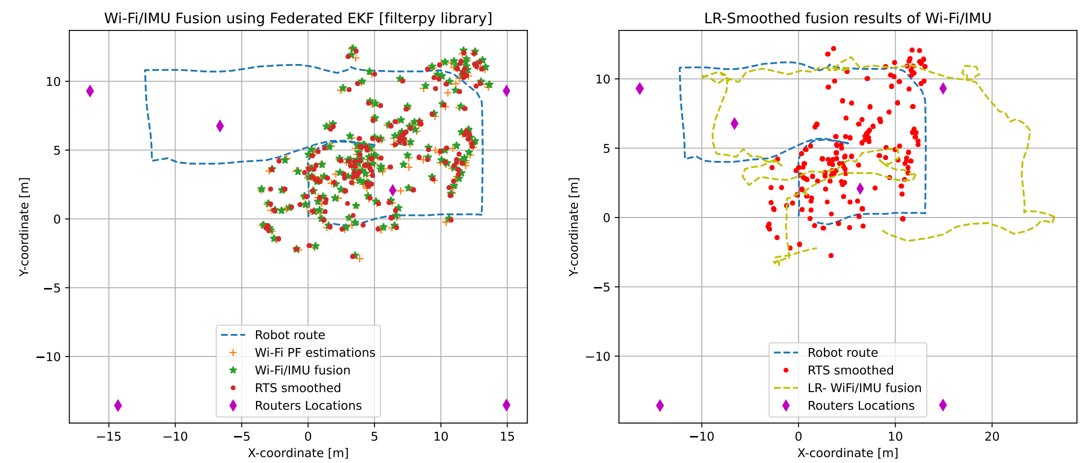


**Figure 6:** Results of Wi-Fi positioning before and after applying Linear Regression algorithm.

routers for positioning applications, or 3) erroneous software scanner which holds the RSSI values for too long time before refreshing to new readings, 4) the extremely dense environment makes it super-challenging for Wi-Fi positioning in particular. Again, mitigating nearly 30% of the error using LR algorithm is another evidence that machine learning algorithms could be employed as standalone positioning techniques, provided that a proper training process was made.

## 1. Summary

To summarize what have been achieved in this study, a cumulative distribution function plot was sketched for both UWB IPS and Wi-Fi IPS to note the difference between all utilized methodologies and algorithms from a very high perspective, as shown in Figure 7.

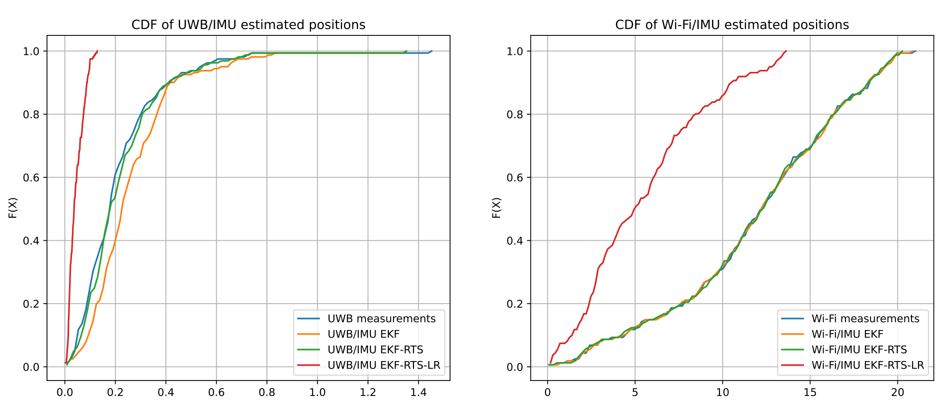


**Figure 7:** Cumulative distribution function plots for both UWB and Wi-Fi IPSs.

Both red curves in the two plots are having the most steep slope amongst their counterparts, meaning that the LR-smoothed fusion method can yield the best and most accurate results even in dense industrial situations, which is a very fitting solution to combating NLOS conditions. The method is proven to be reliable for both IPSs (UWB and Wi-Fi) to facilitate technical operations with precise location information using UWB/IMU, and ensure an acceptable level of performance for human resources tracking using Wi-Fi/IMU, which could be further improved in the future.

**Table 2:** Positioning errors [in meters] of Wi-Fi IPS.

| | Wi-Fi Particle Filter | Wi-Fi/IMU Fusion | Wi-Fi/IMU +RTS | Wi-Fi/IMU/RTS +LR |
|---|---|---|---|---|
| **MAE** | 6.862 | 6.863 | 6.854 | 4.515 |
| **RMSE** | 8.304 | 8.318 | 8.308 | 5.812 |

## V. CONCLUSION

Indoor positioning systems are very crucial for navigational and location-aware applications. Building dedicated IPSs in dense industrial environment requires thorough and meticulous investigations to find the appropriate solution for mitigating NLOS effects and achieve reliable positioning estimations. In this article, we illustrated our work in designing two IPSs, precise UWB IPS for tracking indoor mobile robots, and Wi-Fi IPS to localize human resources inside a complex laboratory environment in Finland. Both loosely coupled IPSs with the aid of an IMU sensor have yielded the best positioning results amongst all other techniques, the highest accuracy achieved by UWB was ranging between 3.7 – 4.5 centimeters, while for Wi-Fi it was ranging between 4.5 – 5.8 meters. For future work, we aim to add a BLE IPS which has been already partially implemented in the lab environment, while investigating more improvement techniques to the existing Wi-Fi IPS.

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