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Fully Coupled Hybrid 802.15.4a UWB/IMU for Indoor Positioning Applications

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Abstract — **This paper presents a fully coupled indoor positioning system combining IEEE 802.15.4a Ultra Wideband (UWB) with inertial sensors. Fully coupled implies that the positioning system not only implements position estimation of the object by fusing the UWB and inertial measurements, but also employs the IEEE 802.15.4a UWB as a wireless communication mechanism for exchanging latest position-based messages between two independent nodes, and thus makes timely remote tracking possible. Two positioning approaches named inertial navigation system (INS) and INS pulse UWB correction are proposed. The fully-coupled positioning system is implemented and tested in two practical cases related to indoor positioning. Experimental results show that the proposed system is capable of realizing both local and remote positioning, and the INS pulse UWB correction approach obtains higher positioning performance when compare to the INS approach.**

Keywords — **IEEE 802.15.4a UWB, IMU, Fully coupled, Indoor positioning.**

I Introduction

A growing attention is currently paid to position-dependent services in indoor environments where satellite-based navigation systems cannot operate. In this context, alternative solutions relying on position-enabled technologies are currently under investigation. As an example, IEEE 802.15.4a Ultra-Wideband (UWB) technology, with large signal bandwidth property, theoretically makes possible the acquisition of accurate temporal measurements, such as the Time Of Arrival (TOA) [1]. For another example, an inertial measurement unit (IMU), which benefits from its regularity and its independence from any existing infrastructure capabilities, makes it particularly be suitable in the context of pedestrian navigation [2]. The adoption of a stand-alone inertial sensor approach to navigation has long been established for various applications in avionics and robotics [3, 4]. However, in complex indoor environments, UWB systems experience multipath phenomena, especially in generalized NLOS conditions, which are prominent and give rise to distorted and bumpy position estimation [5]. Even if the IMU provides accurate position tracking for short periods of time, but drift prone for longer timescales [2]. In order to improve the positioning performance, a number of hybrid indoor positioning systems combining the complementary advantages of UWB and inertial sensors have been proposed [2, 6, 7].

These proposed integration approaches can be classified as loosely-coupled and tightly-coupled. The loosely coupled approach is a solution where the measurements from one or several of the individual sensors are preprocessed before they are used to compute the final results. Tightly coupled approach on the other hand directly uses all the measurements to compute the final position results. However, these approaches are limited in that the nodes are incapable of exchanging positional data with other network nodes given the UWB channel is dedicated to ranging alone. The

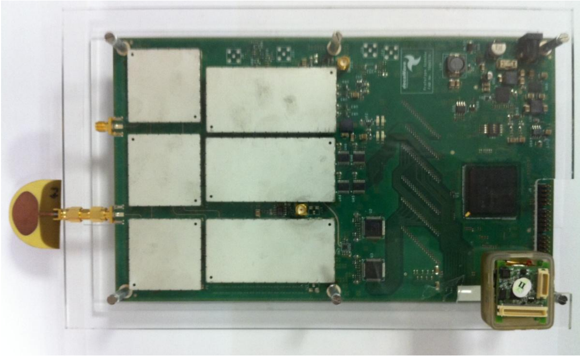

Fig. 1: The sensor unit integrating an IEEE 802.15.4a UWB and an IMU.

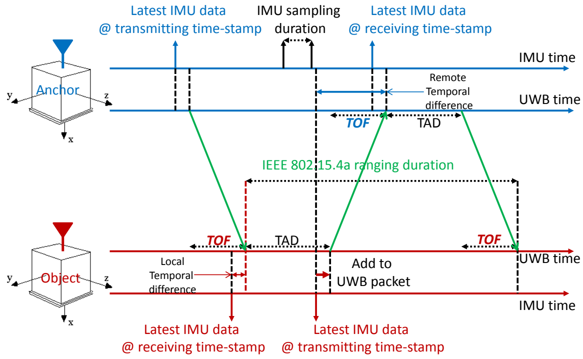

Fig. 2: Fully-coupled data communication and synchronization.

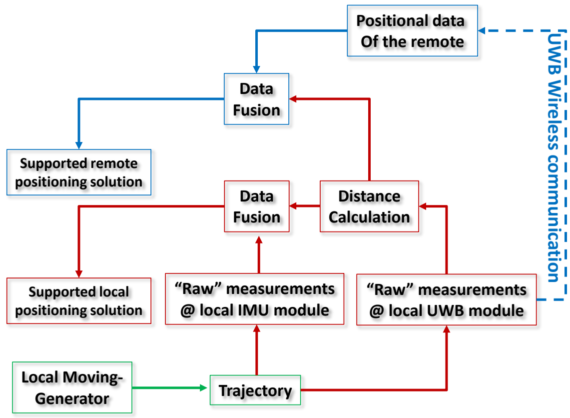

Fig. 3: Fully-coupled architecture.

solution in many cases is to supplement the system with an additional wireless technology, which, in turn, increases the cost and size of the infrastructure and further complicates data synchronization. In this paper we propose a solution to track the object's movement both locally and remotely based on fully coupled sensor fusion of IEEE 802.15.4a UWB and inertial sensors.

II Fully coupled approach

The ability of locally and remotely tracking an object is a requirement of many applications. "Locally" implies that the object is able to self-locate, while "remotely" indicates that the object is tracked by another node, such as an anchor, to which the object is transmitting all the positional data. In order to implement efficient mutual positioning, a "local" and a "remote" synchronization mechanism must be realized. This section gives a detailed solution named fully-coupled sensor fusion based on our setup.

Our setup is based on an IEEE 802.15.4a UWB ranging system, each UWB transceiver is integrated with an IMU to reform a single unit as shown in Fig.1. Each UWB sensor can generate a time-of-flight (TOF)-based ranging measurement employing the symmetric double sided two way ranging algorithm [8]. A group of inertial measurements for inertial navigation could be generated by the IMU with a specific sampling rate [9]. However, these ranging and inertial measurements are not synchronized. The different sampling rates of these measurements is illustrated in Fig.2. Firstly, the TOF-based ranging sampling duration of individual UWB sensor is irregular, due to TOF estimation is carried out at each receiving time-stamp and it is strongly correlated with hardware turnaround delay (TAD) and the varying distance associated with the ambulatory environment. Secondly, considering the IMU components of two independent hybrid modules, it is not possible to assume a synchronous or constant sampling rate, due to elements such as clock drift and asynchronous event triggering.

In this work, for "local" synchronization, see Fig.2, the object completes a TOF estimation at the receiving time-stamp and associates TOF data with the latest IMU data generated locally. The maximum temporal difference between two types of data is the IMU sampling duration, for instance, 1 ms in case of a 1KHz sampling rate.

For "remote" synchronization, the object adds the latest the IMU data generated to the UWB packet which is going to be transmitted to the anchor at the transmitting time-stamp. After wireless communication, when this packet is arrived, the anchor encodes the object's inertial data and associates them with a latest TOF measured at the receiving time-stamp. The maximum temporal difference between the anchor's TOF data and the object's inertial data is equal to the sum of the TOF and IMU sampling duration. In case of typically indoor short-range areas (approximate up to 100m, or 33.3ns of a TOF), with a long IMU sampling duration (1ms), the TOF can be neglected.

In order to estimate both "local" and "remote" positional data at a single node, a fully coupled sensor fusion is used, shown in Fig.3. That is, the latest "raw" measurements of UWB sensors generated at the receiving time-stamp, and at this moment, the latest "raw" sensor measurements generated from local IMU, and the latest positional data of the remote node transmitted through the UWB channel, are then stored in a database when they are temporally aligned. The database is populated by each node communicating in the network enabling local or remote positioning to be made on a continual basis with measurable and compensable temporal offset.

The advantage of using a fully coupled approach are two-fold. Firstly, it can perform positional data exchanging with other network nodes by using the UWB channel, and thus makes both local and remote tracking be possible. Secondly, this reciprocal data distribution allows several nodes to track one another and for each node to consider its mobile neighbors as anchors at intelligently arrived at spatiotemporal points. This approach therefore has the potential to reduce the overall number of anchors needed for positioning.

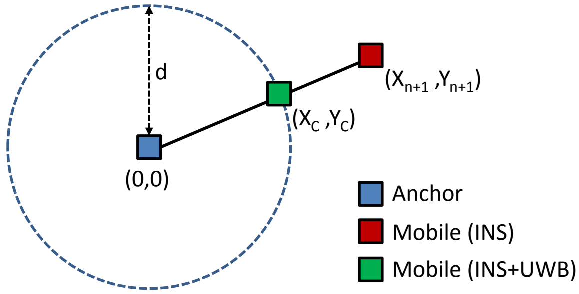

Fig. 4: INS plus UWB correction approach.

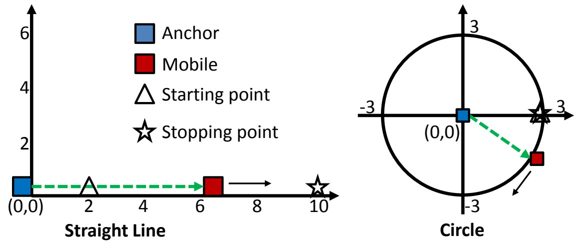

Fig. 5: Experimental scenarios.

III Positioning model

The fully coupled sensor fusion approach briefly introduced in the previous section requires a positioning model of the sensor unit. According to our setup, the IMU consisting of an array of 3D accelerometer, 3D gyroscope, and 3D magnetometer is able to measure the 3D orientation. The IEEE 802.15.4a UWB transceiver can only measure a distance when the signal arrivals. Therefore, there are two positioning models can be used, namely pure inertial navigation system (INS) approach and INS plus UWB correction approach. It is assumed that the anchor represents the origin of a Cartesian coordinate system whose orientation is employed to establish a reference frame.

a) *Inertial navigation*

The position of the object calculated using inertial navigation approach can be expressed as:

$$\begin{cases} X_{n+1} = X_n \pm v_{x,n+1} \bullet dt \\ Y_{n+1} = Y_n \pm v_{y,n+1} \bullet dt \end{cases} \tag{1}$$

Here,

$$\begin{cases} v_{x,n+1} = \bar{v} \times cos(\Phi_{n+1}) \\ v_{y,n+1} = \bar{v} \times sin(\Phi_{n+1}) \end{cases} \tag{2}$$

Here, (X_{n+1}, Y_{n+1}) indicates the next position of the mobile node, (X_n, Y_n) is the current position, dt is the sampling time, $\bar{v}\times$ is the magnitude of its speed, and Φ_{n+1} is the difference between the orientations estimated by the two nodes. It is worth pointing out that, in the previous formula, the sign '+' is necessary in case the mobile node moves forward, the opposite when it moves backward. Although the discrimination between the two movements is trivial due to the presence of a gyroscope in the IMU, for simplicity, it is assumed that the mobile node moves in the forward direction only. Furthermore, even though the speed magnitude could be estimated by means of a double integration of the acceleration (after the transformation from the body to the global reference and a gravity subtraction), it is assumed to be uniform for experiment.

b) *INS plus UWB correction*

Due to the MEMS data would be affected by errors typical of these inertial sensors, such as drift and bias which disturb the estimation of the pedestrian trajectory [2]. To mitigate the trajectory error generated using the equations (1) and (2), we propose a INS plus UWB correction approach as shown in Fig.4.

It extrapolates a line drawn between the anchor located at (0,0) and the position currently estimated by the INS approach (X_{n+1}, Y_{n+1}). The corrected position of the mobile node is taken as the point of intersection (X_c, Y_c) of a circle with center (0,0) and with radius equal to the current UWB ranging measurement d as per the TOF-based ranging algorithm. The point so calculated represents the new estimated position of the mobile node and is taken as (X_n, Y_n) in the subsequent iteration of the INS algorithm in equations (1), (2).

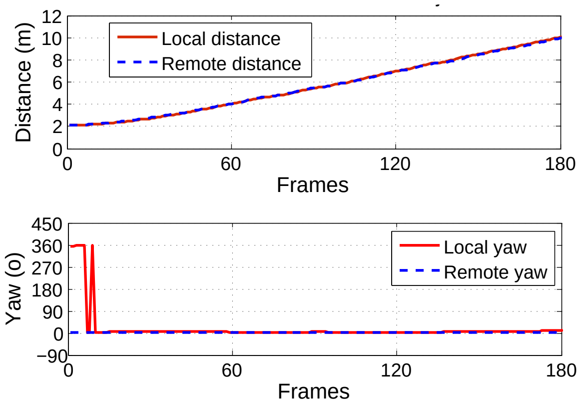

Fig. 6: Positional measurements of the object on a straight line.

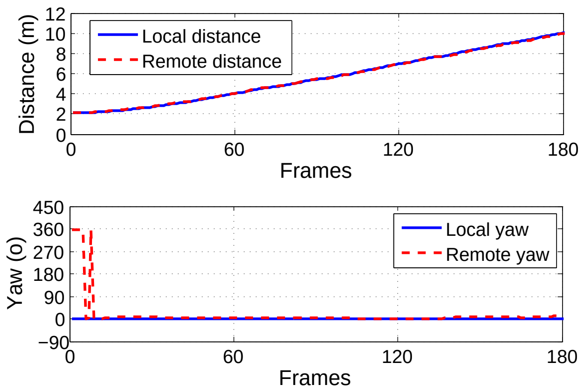

Fig. 7: Positional measurements of the anchor on a straight line.

IV Practical implementation

The proposed fully-coupled system has been used to track a test object moving around in a relatively large conference room in Tyndall National Institute, approximately $12 \times 10 \times 2.5$ m in size. The experiment entails the use of two nodes (for the purposes of the experiment known as the mobile and anchor nodes respectively), each comprising of an IMU and a UWB module, see Fig.1. More specifically, the IMU module is based on the modular Tyndall 25mm mote platform [9], which consists of an array of 3D accelerometer, 3D gyroscope, and 3D magnetometer coupled with a high resolution analog-to-digital converter (ADC). The UWB prototype, developed by Decawave [10], is the world's first IEEE 802.15.4a standard compliant UWB transceiver. 3D orientation is estimated by the IMU in real-time 10 times per second employing the well established low computational methodology in [11]. The 802.15.4a UWB module, depending on range, calculates the distance between the two transceivers approximately every 0.6 seconds. Inertial and ranging data from remote and local nodes are synchronized from both sides by means of the fully-coupled approach in Fig.3.

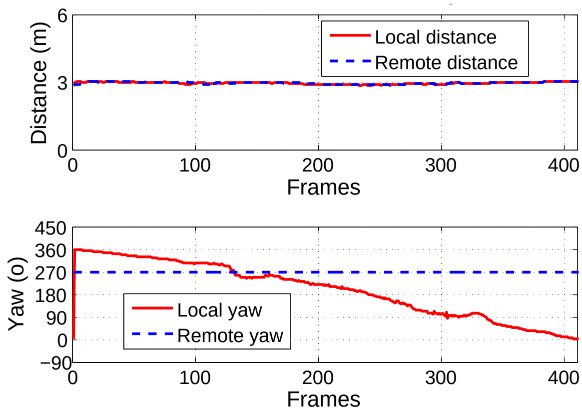

Fig. 8: Positional measurements of the object on a circle.

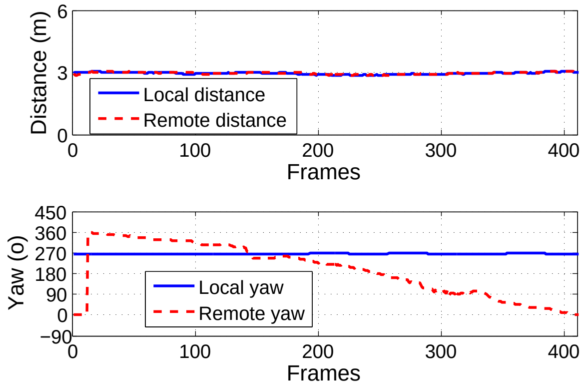

Fig. 9: Positional measurements of the anchor on a circle.

We implemented two experimental scenarios, see Fig.5, one is the object moves on a straight line form the starting point (2,0) to the stopping point (10,0). The other is the object moves on a circle with a radius of 3m, starting from the point (3,0) and stopping at the same point. The anchor is mounted at a specific point which is chosen as the origin (0,0). The real-time position estimates are shown on a 2D plane.

a) local and remote positional measurements

From Fig.6 to Fig.9, the local and remote positional measurements (ranging and orientation) are presented. Fig.6 shows positional measurements collected during the test on a straight line by the object. The same information of the object moving on the straight line measured by the anchor is illustrated in Fig.7. It is easy to see that, as expected, the local data at the object is closely related to the remote data available to the anchor and vice versa. Fig.8 describes positional measurements collected during the test on a circle by the object. The distances measured are very accurate using the UWB signals and the yaw angle changes from 0^o to 360^o. The anchor being stationary throughout observes no local change in yaw during the experiment. The positional measurements estimated at the an-

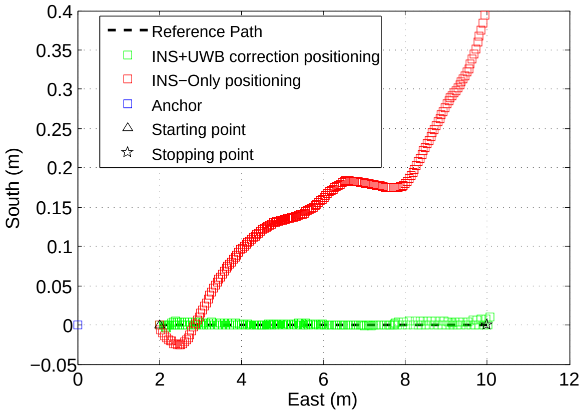

Fig. 10: Positions of the object measured at object on a straight line.

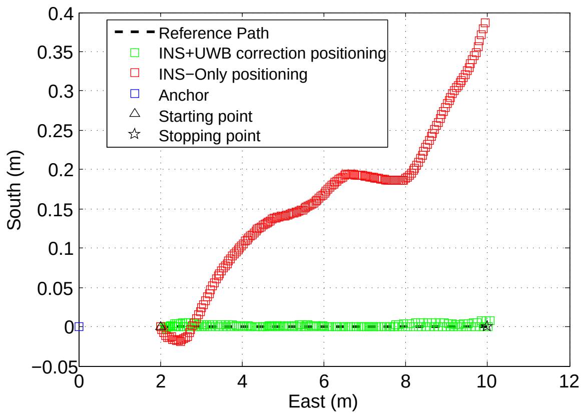

Fig. 11: Positions of the object measured at anchor on a straight line.

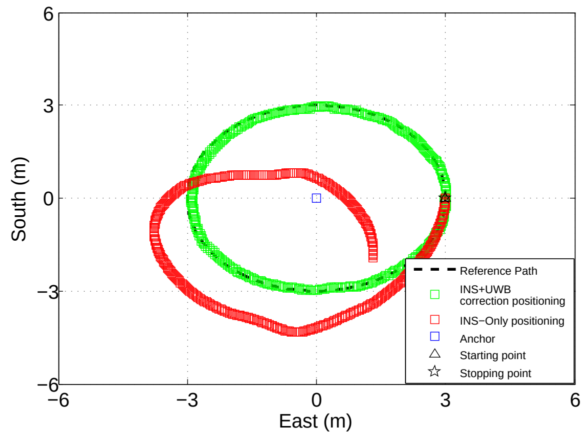

Fig. 12: Positions of the object measured at object on a circle.

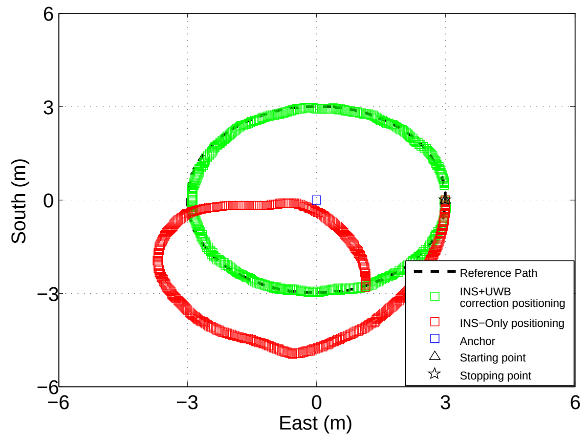

Fig. 13: Positions of the object measured at anchor on a circle.

chor, see Fig.9, are closely the same as the information as shown in Fig.8. Such bilateral mutual and synchronous data sharing is enabled through the utilization of the fully-coupled approach.

b) Local and remote positioning estimation

Using these synchronized positional measurements, the position estimation is carried out by using both inertial navigation system approach and the INS plus UWB approach described in Section III. According to the fully coupled sensor fusion approach, the positioning system is able to implement local positioning at the object and remote positioning at the anchor.

When moving on a straight line, the object uses its synchronized yaw and distance measurements to self-locate as shown in Fig.10. The anchor uses the received positional data of the object and its distance measurements to track the object as shown in Fig.11. It is clearly to observe that, the positioning performance of INS is much lower than the INS plus UWB approach. It again proves that the UWB is a promising technology for indoor ranging and positioning.

Fig.12 and Fig.13 show the position results of the object moving on a circle. Obviously, both INS and INS plus UWB approaches can realize the local and remote position estimation. And, the INS plus UWB approach again is proved which is much stronger than the INS-only positioning approach.

V Conclusions

In this work, a hybrid fully-coupled approach was proposed. This approach can perform positional data exchanging with other network nodes by using the UWB channel, and thus makes both local and remote tracking be possible. Moreover, the reciprocal data distribution allows several nodes to track one another and for each node to consider its mobile neighbors as anchors at intelligently arrived at spatiotemporal points. This approach therefore has the potential to reduce the overall number of anchors needed for positioning.

The positioning models called inertial navigation system approach and INS pulse UWB approach are proposed and integrated into the fully-coupled architecture.

This fully-coupled positioning approach was investigated through an integration of IEEE 802.15.4a complaint UWB transceiver and inertial sensors. The experimental results show the local and remote positional data could be synchronized by the use of fully-coupled approach, and INS pulse UWB approach can significantly improve the positioning performance of inertial navigation approach.

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