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Indoor Localization Using Pedestrian Dead Reckoning Updated with RFID-Based Fiducials

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Abstract— **We describe a low-cost wearable system that tracks the location of individuals indoors using commonly available inertial navigation sensors fused with radio frequency identification (RFID) tags placed around the smart environment. While conventional pedestrian dead reckoning (PDR) calculated with an inertial measurement unit (IMU) is susceptible to sensor drift inaccuracies, the proposed wearable prototype fuses the drift-sensitive IMU with a RFID tag reader. Passive RFID tags placed throughout the smart-building then act as fiducial markers that update the physical locations of each user, thereby correcting positional errors and sensor inaccuracy. Experimental measurements taken for a 55 m x 20 m 2D floor space indicate an over 1200% improvement in average error rate of the proposed RFID-fused system over dead reckoning alone.**

I. INTRODUCTION

There currently exist a wide variety of solutions to the indoor localization and tracking problem. Current solutions include computer vision camera systems [1], ultrasound [2] or passive infrared sensors (PIR) [3], wireless sensor networks (WSN) [4], and ultra-wideband (UWB) RF propagation [5]. Each of these has significant drawbacks, such as privacy concerns, multi-user error, poor resolution, and complex installation, respectively. One common solution for tracking the physical location of individuals is the use of personal dead reckoning (PDR). Unfortunately, unaided PDR exhibits significant sensor drift limitations [6], preventing it from being used effectively over any reasonable time period. Conventionally, multiple solutions can be combined in order to achieve better overall results. In this work, we combine PDR with passive RFID updating to provide additional fiducial information, resulting in significantly improved localization accuracy.

1) Application of Indoor Localization to Medicine: The ability to track the locations of multiple individuals in an indoor environment has many relevant applications in medicine. For example, locating patients in their homes is important for providing context-aware services such as medication reminders [7]. Long term location, activity, and behavioral tracking of elderly patients at home enables them to live independently in their homes for a longer duration.

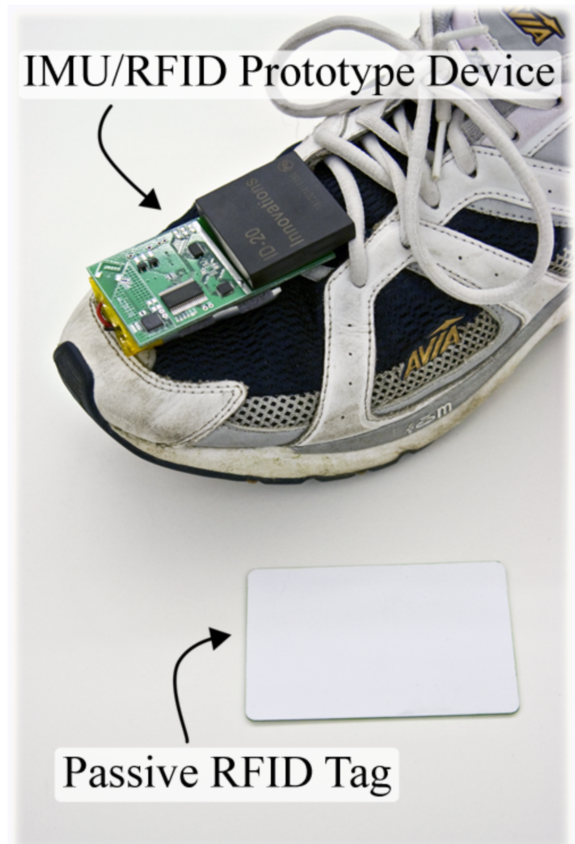

Fig. 1: Equipped prototype device adjacent to a passive RFID tag used as a fiducial waypoint.

Aging in place is accomplished by allowing physicians to easily check on a patient's physical activity levels [8] and evaluate patterns of early cognitive decline [9], [10]. Dementia patients at risk for wandering could have their location updated to care-givers, alerting as soon as the patients have left a pre-defined area. The precise location tracking of doctors, staff, and equipment within a medical complex could also be beneficial for time-critical emergencies that require immediate attention.

2) Personal Dead Reckoning: Dead reckoning devices operate by starting with a known position of the tracking device and then measuring inertial changes on the device, made possible using an inertial measurement unit (IMU). The IMU typically consists of at least a three-axis accelerometer as well as a three-axis gyroscope. In certain systems an IMU will also include a three-axis magnetometer to detect the

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Earth's magnetic field, but for many indoor environments this will not work [11]. One major problem with conventional dead reckoning schemes is the drift associated with the individual sensors on the IMU; the zero-rate output (ZRO), also known as the sensor offset, will drift over time [12], [13]. This, along with the imperfections of the measurements for any IMU, lead to small errors in the inertial measurement which are accumulated and compounded during position calculations. With proper filtering, PDR can be suitable for short-term tracking, but long term localization is extremely difficult [14]. In this work, we implement both Extended Kalman Filter (EKF) [15] and Zero Velocity Update (ZUPT) in order to reduce the noise and drift of the IMU. EKF is a well known filtering method and is discussed in detail later. The ZUPT is a drift-canceling method that requires that the device be foot-mounted, such that during a step, when the device is stationary with reference to the floor, the velocity is reset to zero eliminating most of the drift in the ZRO. While there has been relative success using a similar combination of filtering and correction methods [16], these implementations still exhibit an error rate proportional to the distance traveled. Without a method to update the sensor location directly, the PDR alone is not sufficiently accurate for a long-term implementation of tracking and localization.

3) Radio Frequency Identification: One solution to the localization problem is to distribute low-cost active or passive RFID tags throughout the indoor environment, such as within the smart-home, acting as waypoints that update the PDR. Active RFID localization solutions require the installation of multiple readers; for example, as in [17], a two-meter spaced grid of reference active tags must be placed in the environment. In practice, the primary difference between active and passive tags is the read range. Active tags exhibit a greater read range with a coarser spatial granularity compared with smaller read range, precisely-located passive tags. For our proposed system, we utilize passive tags in order to enable more accurate position estimates as well as lower system setup costs. One potential problem with using passive tags is that the device may not frequently encounter tags placed around the environment. However, the low-cost, small size, and simple setup of passive RFID tags are significant advantages in our approach. RFID tags also exhibit an additional benefit that each location contains a unique ID number that is mapped to a particular location in the home. As an individual equipped with this device moves around his smart-home, he will pass near these fiducial waypoints. When this RFID fiducial is encountered, the location of the device unique to the wearer is resynchronized. Thus, fiducial updating not only provides multi-user localization information, but also allows additional drift in the sensors to be removed.

Hence, the sensor combination of the PDR and RFID solutions results in an excellent match up of complementary strengths. PDR is utilized for short-term tracking between accurate and precise location updates from the RFID tags. Because the device is foot-mounted for the ZUPT, the RFID tags should be placed on the ground in commonly traversed locations. For instance, these might be pinch-point locations such as doorways, kitchen, hallways, or other common places that will likely be stepped on, increasing the likelihood of an update.

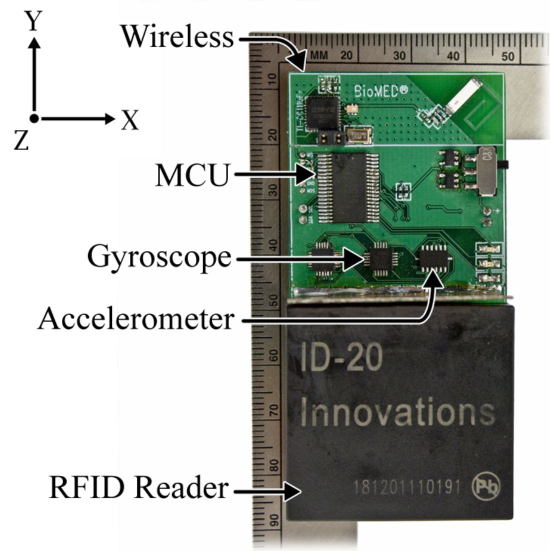

Fig. 2: IMU/RFID prototype device

II. System Description

A. Hardware Overview

The complete PDR system with the RFID device is shown in Fig. 2. The IMU consists of a three-axis accelerometer, three-axis gyroscope, and a three-axis magnetometer. All of the tri-axial measurement components are oriented on the board so as to be co-axial along each of their X axes. Ignoring the small distances between the sensor packages, the device can be assumed to have a single axis system. As pictured in Fig. 2, the device's X axis is horizontal (positive is right), the Y axis is vertical (positive is up), and the Z axis is through the page (positive is out). The main components of the device are detailed in Table 1. The size of the device is 8cm by 4cm. The completed prototype device costs less than 100 USD in small volume.

1) Theory of Operation: After initialization and calibration routines are performed, the microcontroller (MCU) begins to sample inertial and RFID tag data at 50Hz. The RFID data is sent asynchronously from the ID-20 and is collected using a software-implemented UART on the MCU. Communication with the three inertial sensors is accomplished using the standard I^2C interface. The only other connections to the MCU are the data-ready interrupts. Once a set of data is collected it is sent out using a hardware UART on the MCU through a UART/USB bridge to a computer for back-end data processing.

B. Processing

The inertial and RFID tag information is being processed off board due to computational constraints, cost reduction, and in the interests of decreasing device power usage.

TABLE I: Device Components

Analog Devices ADXL345	
Description	Three-axis Accelerometer
Cost	6.16 USD
Detection Range	$\pm$ 16 g
Power Consumption	35 μw
Invensense IMU3000	
Description	Three-axis Gyroscope
Cost	15.00 USD
Detection Range	$\pm$ 1000 dps
Power Consumption	13 mw
ID Innovations ID-20	
Description	125 kHz RFID Reader
Cost	34.95 USD
Detection Range	$\approx$ 10 cm
Power Consumption	<150 mw
Texas Instruments MSP430	
Description	Microcontroller
Cost	7.35 USD
Power Consumption	590 μw
Texas Instruments CC1110	
Description	Wireless Interface
Cost	2.75 USD
Power Consumption	$\approx$ 45 mw

1) Data Filtering: Footfalls are detected by examining the largest singular value of the accelerometer variance. When a footfall is detected, a Kalman filter is used to update estimates for position, velocity and orientation.

Suppose n samples are taken between footfall updates. Let $Q_1, \ldots, Q_n$ be the rotation matrices from the body frame for those samples. Error in velocity accumulated during the previous step is assumed to be caused by two sources, an error in the accelerometer offset $\hat{da}$ and an error in the estimate for gravity $\hat{g}$. These result in a velocity error of:

$$\hat{v} = dt \begin{bmatrix} \sum_{k=1}^{n} Q_k & nI \end{bmatrix} \begin{bmatrix} \hat{da} \\ \hat{g} \end{bmatrix} \tag{1}$$

The foot is assumed to have zero velocity during the footfall update so a Kalman filter is used to estimate $\hat{da}$ and $\hat{g}$ with a measured velocity of zero and an observation matrix:

$$H = \begin{bmatrix} \sum_{k=1}^{n} Q_k & nI \end{bmatrix} \tag{2}$$

The position over the previous footfall is then re-integrated using the estimates for $\hat{da}$ and $\hat{g}$.

In addition, the foot is assumed to be experiencing no acceleration during the footfall update so the measurement of acceleration can be taken as a measurement of gravity in the body frame, $\overline{g_b}$. Let p be the modified Rodrigues parameters associated with rotation to the body frame during the footfall update and let $Q(p)$ be its associated rotation matrix. Then gravity in the body frame is:

$$g_b = Q(p)g \tag{3}$$

An extended kalman filter is used to update the estimate for p using the measurement function:

$$h(p) = Q(p)g \tag{4}$$

When an RFID fiducial is encountered, an affine transformation is formulated which rotates and scales the difference between each point and the position of the last RFID tag such that the current position is mapped to the RFID fiducial. This transformation is then applied to the previous positions.

III. Method

As an initial test of the proposed method, a portion of the second floor of Oregon State University's Kelley Engineering Center was equipped with four passive RFID fiducial markers, with a volunteer walking a simple rectangular path. The small RFID tags (85mm x 54mm x 1mm) were adhered flat on the floor at the corners of the measured rectangle (Fig. 3). One person instrumenting this track with passive tags and measuring their relative locations required no more than 10 minutes. A twenty-one year old male volunteer was outfitted with this device by attaching it to his shoe. The device was secured as flat as possible on the toe of the right shoe and oriented so that the positive Y-axis was forward, the positive X-axis was to the right, and the positive Z-axis was up. The volunteer was then asked to make three closed loops around the course. In this preliminary run, the wearer was instructed to attempt to step on the tags, but not to stop at them.

IV. Results

The plotted results of the initial test run appear in Fig. 3. The solid line indicates the position solution provided by PDR alone. The drift of the uncorrected IMU is obvious after only 15 m, which is typical for unaided PDR [18]. The corrected position solution is shown by the dashed line. The closed-loop error in this system is less than 10 cm independent of the distance traveled, due to the use of fiducials as the start and end points. The average error of the PDR only path was 5.91 m from true path with a maximum error of 19.11 m, while the average error of the fiducial updated path was 0.47 m from the true path with a maximum error of 1.77 m.

V. Future Work

Determining the minimal number of RFID fiducial updates needed for patient tracking is critical for determining the required number of tags to be placed around the home. Note that this metric is highly dependent on the home layout and patient movement activity. At the extreme, one possibility would be to simply place as many passive RFID fiducials within the home as possible, but this may incur higher cost and complexity for the installation. An alternative method would be to increase the RFID fiducial update frequency by using both active and passive tag RFID fiducials. For example, the current passive tags exhibit a small reader range (approximately 12cm) which allows for high precision updates, but also unfortunately reduces the probability of an update. Low frequency (125 kHz) battery-powered active

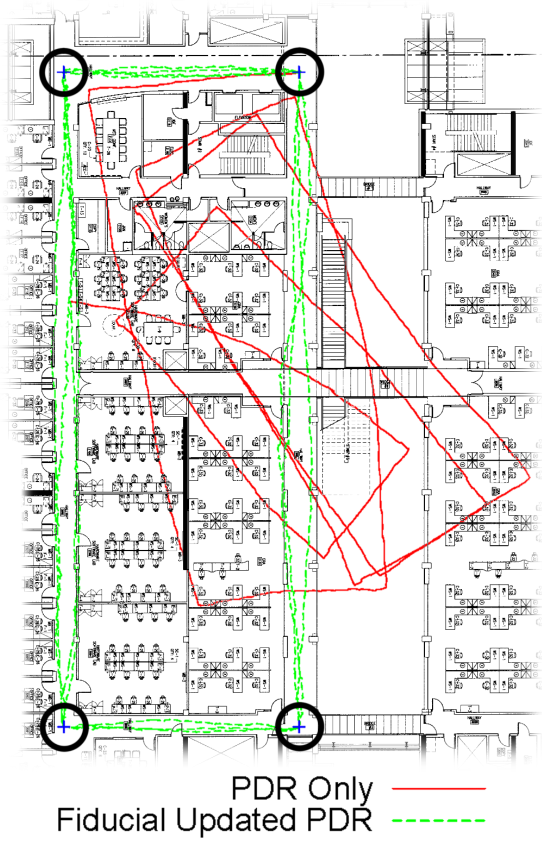

Fig. 3: A simple rectangular track of 54.25 m X 19.5 m. The RFID fiducial markers, indicated with circles, are seen at the corners of the rectangle.

tags, with medium read range, are interoperable with the same hardware used for the passive tags. Additional filtering methods would be required to account for the reduced precision of the updates. The combination of active and passive tags would likely decrease the total number of tags required and increase the fiducial updates and accuracy of the PDR system.

VI. Conclusions

The work described in the paper represents the preliminary testing and results of our RFID fiducial updated PDR method and our ultra low-cost prototype IMU and RFID reader device. We have shown that the use of RFID fiducials as location updates to supplement and correct PDR may be a cost effective and accurate method for tracking multiple individuals in smart-home environments.

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