Long-term Performance Evaluation of a Foot-mounted Pedestrian Navigation Device

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***Abstract*—In this paper, we present a long term experimental study performed on a foot mounted pedestrian navigation device, the Osmium MIMU22BTP, which is based on the OpenShoe platform. The aim of the study is to investigate the performance that can be expected in mass market applications. Accordingly, we investigate the error characteristics over a large number of tracking devices and their alternative mounting schemes, over several wearers, and over different walking scenarios. By a massive data collection corresponding to more than 150 km of elapsed walking distance over almost 1,000 independent tests, the law of large numbers provides us with illustrative rule-of-thumbs for the tracking performance in realistic use cases. We observe no outlier performance and relative errors less than 4% in 95% of the test-cases, indicating its potential for a variety of indoor Location Based Services (LBS) and IoT applications based on foot-mounted inertial sensing and dead reckoning. The experimental findings are validated with long distance walks.**

Keywords*—*Foot mounted sensors; indoor navigation; pedestrian dead reckoning; IMU; indoor location based services; IoT

I. Introduction

Advancement in micro electro mechanical systems (MEMS) fabrication technology has paved the way for MEMS inertial sensors based miniaturized navigation devices, targeted towards battery operable wearable applications such as foot-mounted pedestrian navigation. Many such foot-mounted pedestrian navigation devices have been reported in literature during the last decade, and lately a few off-the-shelf products have been released into the market. Such foot-mounted navigation devices can be used to track pedestrians without prior information of the environment and without any pre-installed infrastructure. Under such conditions tracking accuracy of the devices under varying environmental factors and use cases become critical [1], [2].

The MEMS inertial sensors, i.e., accelerometers and gyroscopes, suffer from internal noises which result in cubically growing position error with time, when navigational equations are solved. Effect of slight errors in acceleration and rotation measurements may finally lead to totally misleading position estimates which can make inertial sensors based navigation systems useless [3]. One method to reduce the error growth in a foot-mounted navigation device is the so called zero velocity update (ZUPT) approach. The ZUPT consists of identifying step occurrences by detecting foot's standstill instant. This is followed by estimating and correcting errors by making use of any non-zero velocity detected at the time instant of step detection. This approach reduces errors in position and heading estimates at every detected step and prevents them from growing exponentially with time [4], [5], [6].

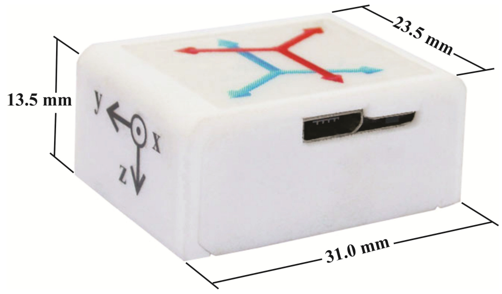

Fig. 1: The Osmium MIMU22TP: A multi-IMU (MIMU) based foot-mounted device for zero-velocity-update (ZUPT) aided pedestrian navigation. The coordinate axes of its reference frame is depicted on its left side wall.

Tracking performance of the foot-mounted tracking device depends upon number of factors which could influence the way hardware and the algorithm operate. Some of the factors which could influence the tracking performance of a ZUPT-aided foot-mounted navigation devices are type of shoes, device's mounting scheme, wearers' personal traits, walking surface, path profile, walking speed, environmental conditions, etc. These physiological, psychological and environmental factors typically influence gait of a person and hence have direct effect on the performance of a foot-mounted inertial navigation system [7].

In this paper, we present long term performance evaluation of a ZUPT-aided foot-mounted tracking device, the Osmium MIMU22BTP, under semi-controlled environment. The Osmium MIMU22BTP is a versatile embedded system for rapid prototyping, research and education [8]. Limited testing of the device has been reported earlier for single foot and dual foot mounting schemes, under optimized and well controlled test environment [8]. In this paper, we present testing under realistic scenario.

This paper is organized as follows. Section II gives an overview of the device under test, i.e. the Osmium MIMU22BTP. The experimental design setup and the performance metrics used for result analysis are presented in Section III. Results are presented and discussed in Section IV. Conclusion of the study is outlined in Section IV.

II. Device under test - The Osmium MIMU22BTP

The Osmium MIMU22BTP, shown in Fig. 1, is an IMU-array based miniaturized foot-mounted pedestrian navigation device, which has applications in infrastructure-free indoor navigation as required in first responders safety systems used for disaster management. The device also has applications in workforce management of a large warehouse, gait analysis of patients suffering from movement disorders, autonomous robotics, land survey, assisted living etc. The device is based on the OpenShoe platform whose designs are released under the permissive open source Creative Commons Attribution 4.0 International Public License [9].

The Osmium MIMU22BT has a simple data interface that outputs Pedestrian Dead Reckoning (PDR) data at every step. In other words, the device detects steps of its wearer, computes displacement and heading of each detected step with respect to the previous one and transmit it over Bluetooth interface to the application platform for construction of the tracked path as shown in Fig. 2 [8].

The key components of the MIMU22BTP are four 9-axis IMUs, a 32-bits floating point microcontroller, a Bluetooth v3.0 module, micro-USB connector for data communication and an on-board Li-ion battery power management circuitry. The device is programmable through JTAG interface. A barometer and a flash memory are also part of the hardware, but are not used for pedestrian tracking. The magnetometers of the IMUs are also not used.

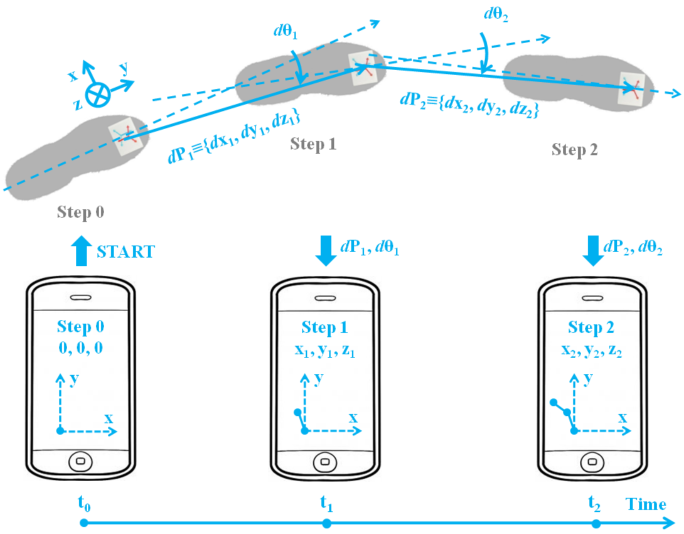

Fig. 2: Pedestrian Dead Reckoning (PDR) is simplified with the foot-mounted Osmium MIMU22BTP. The device starts transmitting location data at every step, on receiving start command from the application platform.

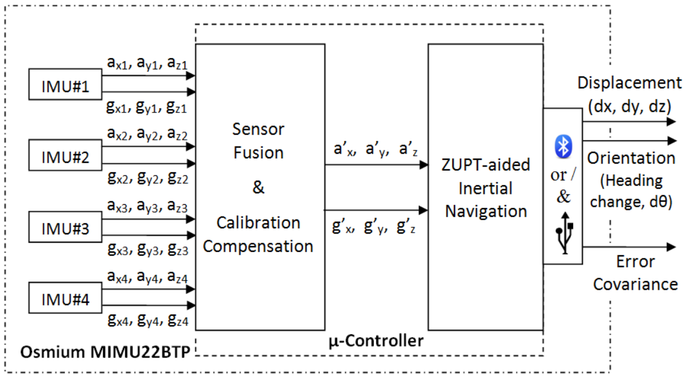

Fig. 3: Block diagram of the Osmium MIMU22BTP: Data from multiple IMUs are sampled, fused, calibration compensated and undergo navigational computation to produce displacement and orientation information.

Multiple IMUs enable data fusion from multiple inertial sensors to bring down the independent stochastic errors and hence improves the tracking performance [10]. Presence of the on-board floating point processing capability allows sensors to be sampled at maximum allowable rate and carry out the data fusion and navigational computation inside the device as illustrated in Fig. 3. The device therefore becomes capable of transmitting low rate PDR data at every step, over wireless interface. Thus the device can be easily integrated with a processing platform, with the help of simple application program interfaces (APIs). The device can easily be attached to the shoe and with the help of an application on the processing platform, it starts collecting data to give relative coordinates of the tracked path.

III. Experiments

A. Design of Experiment

The experiments presented in this paper were designed in such a way that the tracking performance of the devices is evaluated for a range of usage conditions in a semi-controlled way. Each experiment was conducted with a single device. Two different types of test tracks were chosen to perform the experiments, are shown in Fig. 4. There are two categories of test-cases. One is straight line to-and-fro walk consisting of 180° turns and the other is three rounds of a closed loop. Start and stop points were same for all the test-cases. The tracks were marked with start (or stop) points. The wearer placed his foot, which had the device attached, on the start point and started collecting tracking data from there. At the end of the test case, the wearer placed the same foot at the start point and stopped collecting data. The path of the test tracks were marked. The wearer ensured no or minimum deviation from the marked path while maintaining natural gait. All the tests were performed on a plane, with zero or no noticeable variation in elevation. The actual length of the tracks was measured using measurement tape.

Twenty two units of the Osmium MIMU22BTP were used to perform the experiments, which lasted for nearly ten months, starting from July'14 to April'15. All the wearers

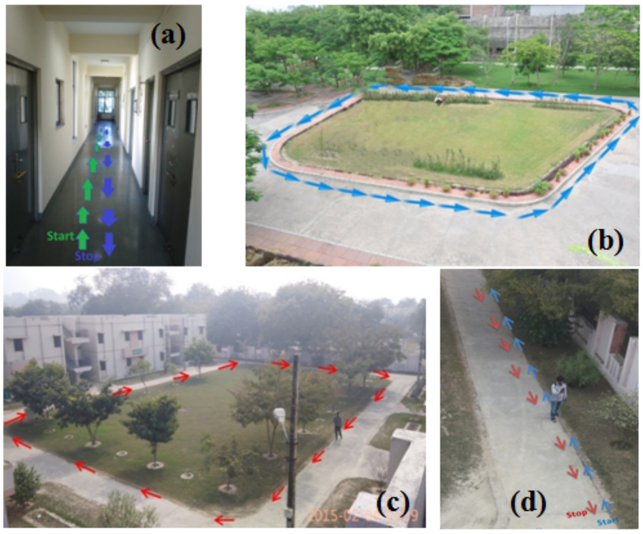

Fig. 4: Bird eye view of the test tracks. Test-cases consisted of (a) Three to-and-fro walks of a corridor of one side length 17.11 m. (b) Traversing thrice a grass lawn with 81 m periphery, as marked (c) Traversing thrice a rectangular field of periphery 129 m, as marked (d) Two to-and-fro walks of a straight line path of one side length 26 m.

were having normal gait, but varying Body Mass Index (16.2, 21.2 and 25.8, respectively). Jogging and trekking shoes were chosen with the two possible mounting schemes – on the front part and on the heel wall of the shoe as shown in Fig. 5. Walking speed range was 4 kmph to 6 kmph. The ambient temperature ranged from 5°C to 40°C during the experiments.

Calibration of the devices was performed under static conditions by placing the devices with different orientations and exploiting the direction of gravitational force. This is achieved by placing the module inside a twenty faced polyhedron - icosahedron [11]. The calibration method estimates inter IMU misalignment and the gain, bias and sensitivity axis non-orthogonality of the accelerometers, under static conditions for the IMU array system. For the experiments, each device was calibrated only once. Once the devices were calibrated, multiple tests were performed with the same calibration data.

The devices were allowed to reach a steady temperature before the tests were carried out by allowing a warm-up time of nearly two minutes. We designed a data recording Android application DaRe and installed it on a smartphone. The device was connected wirelessly via Bluetooth with the

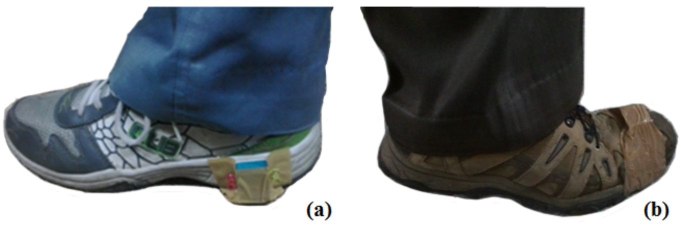

Fig. 5: Mounting schemes and types of shoes (a) Attached to heel wall of a jogging shoe (b) Mounted on the front portion of a trekking shoe.

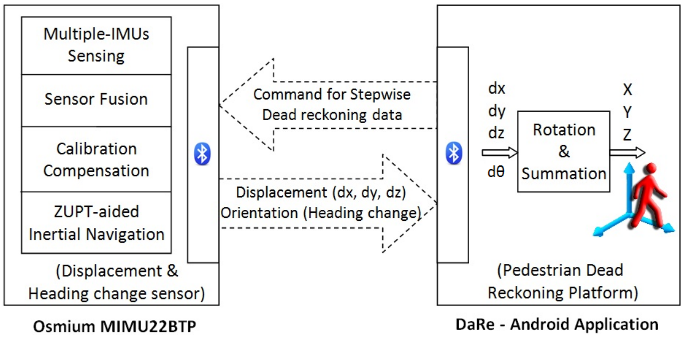

Fig. 6: The Pedestrian Dead Reckoning (PDR) system consisting of the foot-mounted pedestrian navigation sensor, The Osmium MIMU22BTP, and the interfacing Android application DaRe. MIMU22BTP transmits requested data in response to an appropriate command from DaRe. DaRe constructs tracked path using stepwise PDR data from MIMU22BTP.

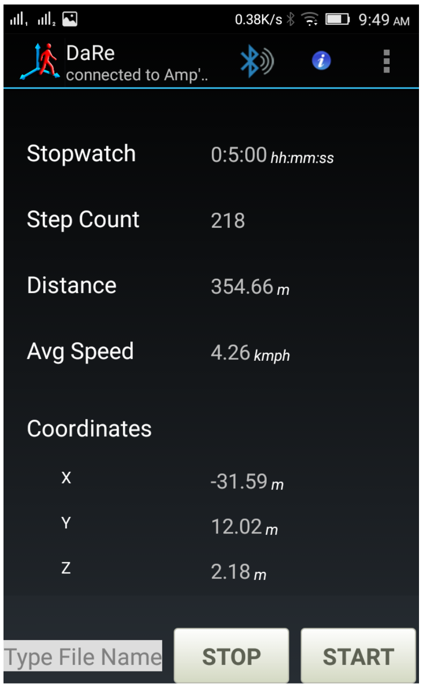

Fig. 7: DaRe - Data recording application for Android devices. DaRe saves the output in a text file which can be accessed for further analysis. A free version of DaRe is available in Google Play Store for installation.

smartphone which the wearer carried during testing. The stepwise dead reckoning data for the test-cases were collected on the smartphone. The PDR system consisting of the foot-mounted Osmium MIMU22BTP and the Android application DaRe is illustrated in Fig. 6. DaRe constructs the traced path by computing steps' coordinates as shown in Fig. 7 and stores them in a text file, in the phone's memory. The output files were later transferred to a computer for data analysis.

Fig. 8 and Fig. 9 show sample estimated paths. The wearer walked on the highlighted paths for three times in a go. Effect of drift on the estimated path is visible in Fig. 9(b). We wish to emphasize that all the results presented in this paper are obtained by MIMU22BTP only, i.e. without maps or any other aiding technology like GPS, WiFi etc.

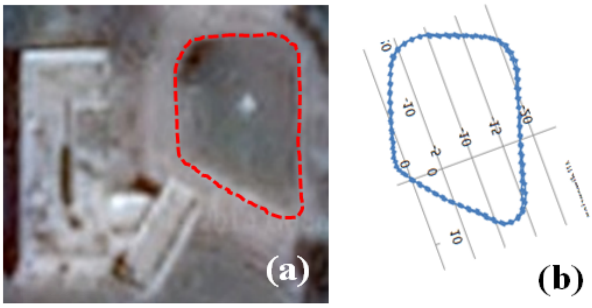

Fig. 8: A test track (a) Satellite view of a test track. Red dashes indicate the actual path traced by the wearer. (b) Path as estimated by the tracking device.

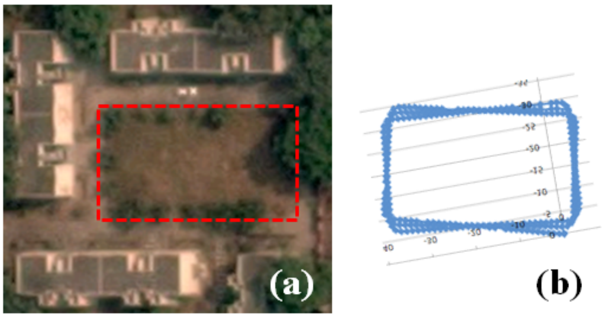

Fig. 9: A test track (a) Satellite view of a test track. Red dashes indicate the actual path traced by the wearer. (b) Path as estimated by the tracking device.

B. Benchmarking Performance Metrics

Due to inherent errors and noise, the estimated stop points are never same as the start points. We refer the error in estimation of stop points as drift in the estimated path. Similarly the distance measured by the tracking device could be marginally different than the actual distance walked by the wearer. Typically the sensors are lesser accurate in the z (vertical) direction. Therefore tracking devices are also evaluated for errors in elevation estimates. Thus we choose three performance metrics to benchmark the tracking performance of the devices [7]:
(i) *Drift Error* (%): Distance between start and stop points per 100 m distance walked.
(ii) *Distance Error* (%): Distance measurement error per 100 m distance walked. Positive value indicates that the device has measured more distance than the actual.
(iii) *Height Error* (z-error) (%): Change in measured z value per 100 m distance walked. Negative value indicates that the position estimated by the device is above ground.

The experiments were conducted on plane surfaces, for all the path profiles. Therefore only x-y coordinates are considered in calculating measured distance and drift.

IV. Results & Discussion

Total 834 tests were performed covering 169.24 km aggregate. The experimental setup is summarized in Table I.

We statistically analyze the results in two different ways by classifying them based on (i) number of test-cases as in Fig. 10 and (ii) distance walked as in Fig. 11. Fig. 10 (a), (b) and (c) show the error (Drift, Distance, and Height) frequency. For example, Fig. 10(b) shows that nearly 2% of the total test-cases have resulted in Distance-error between -2.75% & -2.5% and so on. Fig. 11 (a), (b) and (c) show the error distribution with the distance walked. For example, Fig. 11(a) shows that the total distance walked in the test-cases which reported Drift-error between 0.60% & 0.69%, is approximately 8 km.

TABLE I: Summary of the experimental setup

Device under test	Osmium MIMU22BTP
Test tracks	(a) Straight line walks consisting of several 180° turns (b) Closed loop walks with the path traversing multiple times
Total number of test-cases	834
Total distance walked	169.24 km
Number of devices subjected to testing	22
Device mounting scheme	One device per person, attached to (a) Heel wall (b) Front of the shoe
Testing time span	July'14 to Apr'15 (10 months)
Wearers' Body Mass Index	(a) 16.2 (b) 21.2 (c) 25.8
Type of shoes	(a) Jogging shoes (b) Trekking shoes
Ambient temperature range	5°C to 40°C
Walking speeds	4 kmph to 6 kmph

Note that Drift-error is always a positive number because it is the distance between start and stop points, whereas distance estimated by the device could be less or more than the actual value. Similarly, the position of end point estimated by the device could be above or below ground. Drift error seems to be following Chi-Square distribution, whereas Distance-error and Height-error distributions look like Gaussian. The Distance error is biased towards negative. In other words, estimated average distance is less than the actual one. This is due to implementation of the ZUPT algorithm. Similarly Height error distribution is also biased towards negative. This is also due to implementation of the ZUPT algorithm.

Error (Drift, Distance and Height) ranges for 95% of the performed tests and 95% of the distance walked are presented in Table. II. In simple words, 95% of the tests and 95% of the distance walked fall in these ranges. It is straight forward to obtain 95% range for Drift error. The 95% ranges for Distance and Height errors are chosen such that 2.5% of the tests (or same proportion of the distance walked) are below the 95% ranges and the same proportion above.

There is possibility that steps of the wearer have not fallen on the marked path every time. This might have added very small error, say 0.1% to 0.2%, to the total measurement.

TABLE II: 95% data range for the chosen performance metrics.

Performance Metric	**Range for 95% of test-cases**	**Range for 95% of distance walked**
Drift Error	0.00% to 3.65%	0.00% to 3.8%
Distance Error	-2.75% to 2.57%	-2.87% to 2.49%
Height Error	-3.95% to 2.66%	-3.71% to 2.53%

In order to validate the usefulness of experimental findings, few long distance walks were conducted. Two such walks are shown in Fig. 12 and Fig. 13. The various errors are mentioned in Table III. The errors for these walks are found

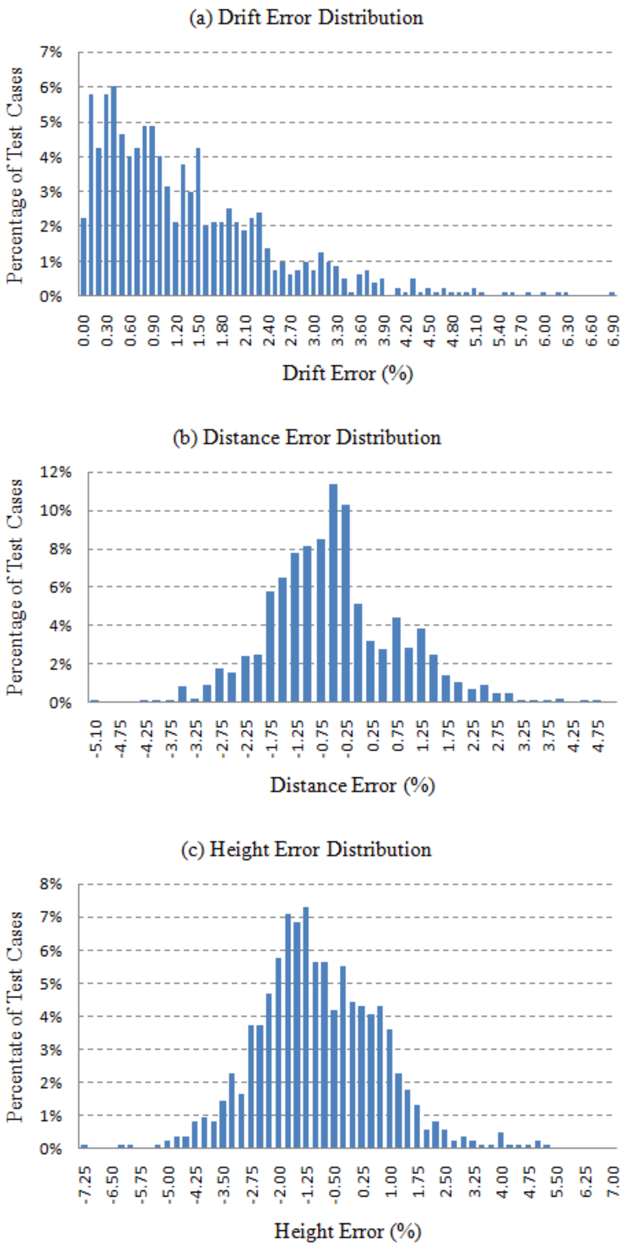

Fig. 10: Statistical representation of errors, based on number of test-cases. Each test-case is categorized on the basis of errors (Drift error, Distance error and Height error) obtained. The histograms are obtained by plotting proportion of total test-cases with errors falling in a common error range.

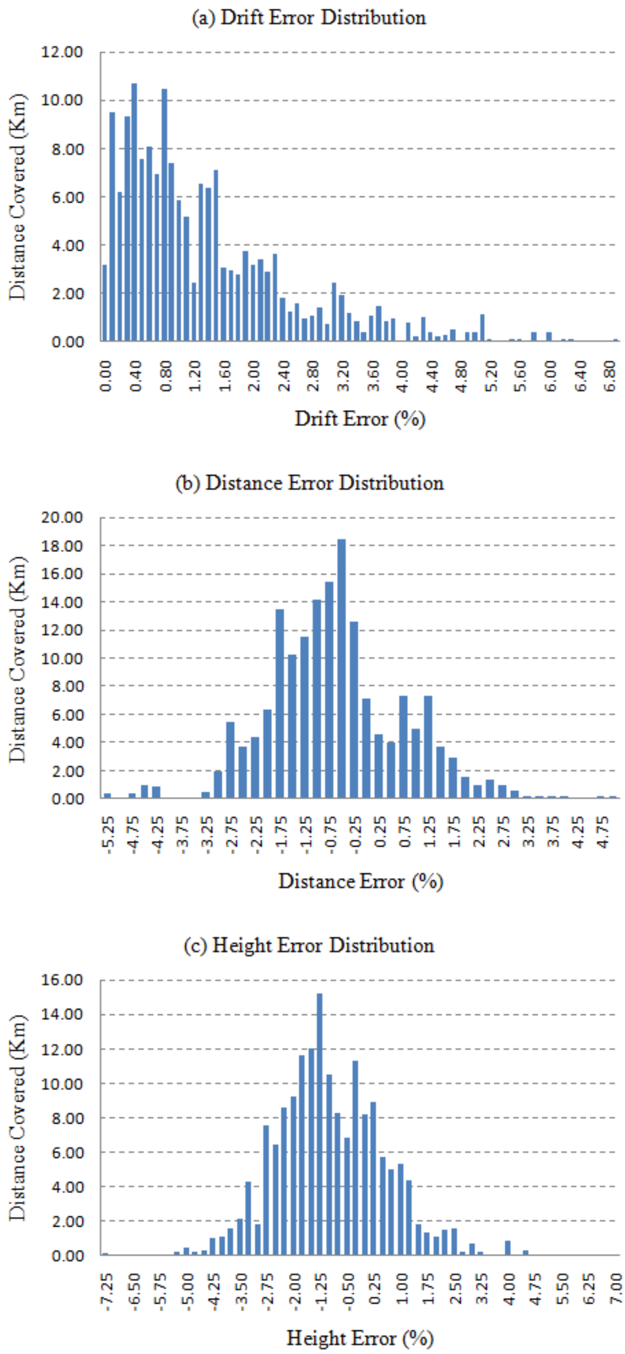

Fig. 11: Statistical representation of errors, based on distance covered. Each test-case is categorized on the basis of errors (Drift error, Distance error and Height error) obtained. The histograms are obtained by plotting aggregate distance for all the test-cases, having errors in a common range.

within the experimentally obtained 95% ranges. This validates the outcome of the long-term experimental study conducted to evaluate the performance of Osmium MIMU22BTP.

Tracking performance of the Osmium MIMU22BT further improves by using dual foot-mounted configuration [8]. The improvement in overall navigation performance with other aiding technologies like WiFi finger printing [12] and radio mapping [13] has been reported. Application of the Ultra-wideband radios to enhance the performance of such foot-mounted navigation systems has also been reported [14].

V. Conclusion

This paper presents an extensive long-term performance evaluation of the foot-mounted pedestrian navigation device the Osmium MIMU22BTP. The semi-controlled experimental evaluation spanned over ten months period and comprised of two types of test tracks, twenty two units of the Osmium

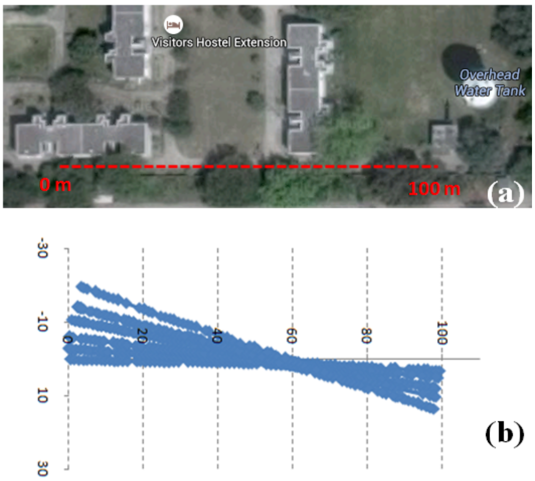

Fig. 12: Validation track (a) Satellite view of a 100m long validation track. Red dashes indicate the actual path traced by the wearer. Distance of 1000 m was covered while walking to-and-fro on the highlighted path. (b) Path as estimated by the tracking device.

TABLE III: Validation: Errors obtained for additional long distance walks.

S. No.	Track	Distance Walked (m)	Error (%)		
			Drift	Distance	Height
1	Straight Line as in Fig. 12(a)	1000.0	2.00	-0.69	-2.21
2	Rectangular as in Fig. 13(a)	1290.0	0.82	-1.63	-3.20

MIMU22BTP and 169 km distance covered by 834 tests. During the test span of ten months, the ambient temperature ranged from 5°C to 40°C. The tests were performed by three persons of different Body Mass Indices, with two different mounting schemes on two types of shoes. No GPS, maps or any other pre-installed infrastructure was used for the tracking experiments. The evaluation of drift, distance and height errors indicates robustness of the performance under realistic scenario. The relative errors are less or equal to 4% for 95% of the performed tests. Finally, errors obtained from two long distance walks validate the outcome of the presented experimental study.

It can be inferred from the findings that the Osmium MIMU22BTP is capable of locating a pedestrian who has walked for 100 m on a plane surface, in a circle of radius 4 m without using GPS or any other tracking aid, in 95 out of 100 times under realistic scenario.

Presented results are obtained with the device attached with single foot. The performance can further be improved by dual foot-mounted configuration and other aiding technologies.

The encouraging test results suggest that the Osmium MIMU22BTP is an eligible IoT candidate for various daily life consumer applications. Innovative use of social media network, cloud services and Big data analysis with the wearable Osmium MIMU22BTP would fuel big innovation and unleash its potential.

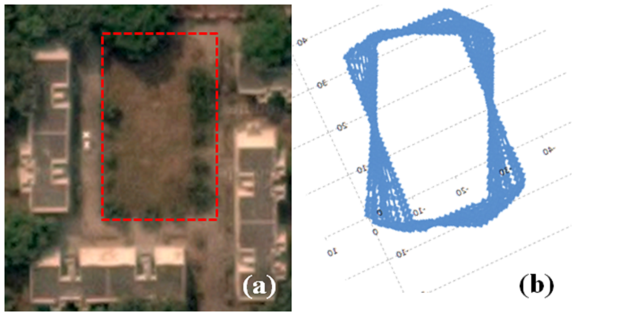

Fig. 13: Validation track, same as of Fig. 9(a). (a) Red dashes indicate the actual path traced by the wearer. The highlighted path was traversed ten times, totalling 1290 m, by the wearer. (b) Path as estimated by the tracking device.

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References

[1] J. Rantakokko et al.,"Accurate and reliable soldier and first responder indoor positioning: Multisensor systems and cooperative localization," *IEEE Trans. Wireless Commun.*, April, 2011, pp. 10-18.

[2] J. Rantakokko, P. Händel, M. Fredholm, and F. Marsten-Eklöf, "User requirements for localization and tracking technology: A Survey of mission-specific needs and constraints," *2010 Int. Conf. on Indoor Positioning and Indoor Navigation (IPIN)*, September 15-17, 2010, Zurich, Switzerland.

[3] K.V.S. Hari, J-O. Nilsson, I. Skog, P. Händel, J. Rantakokko, and G.V. Prateek, "A Prototype of a First Responder Indoor Localization System," *J. of the Indian Institute of Sci.*, Vol. 93:3 Jul.-Sep. 2013.

[4] I. Skog, P. Händel, J-O. Nilsson, and J. Rantakokko "Zero-velocity detection – an algorithm evaluation," *IEEE Trans. Bio-Med. Eng.*, Vol. 57, No. 11, pp. 2657-2666, November 2010.

[5] C Fischer, P Talkad Sukumar, and M Hazas, "Tutorial: Implementing a Pedestrian Tracker Using Inertial Sensors," *Pervasive Comput.,IEEE,* Volume: 12, Issue: 2. Pages 17-27,2012.

[6] E. Foxlin, "Pedestrian tracking with shoe-mounted inertial sensors," *IEEE Comput. Graph. Appl. Mag.* , Vol. 25 Issue 6, pp. 38-46, Nov.-Dec. 2005.

[7] K. G. Sailesh, S. Shyamsundar, A.K. Gupta, and P. Händel, "An experimental study on a pedestrian tracking device," *IEEE Int. Conf. on Electronics, Computing and Communication Technologies (CONECCT)*, July 10-11, 2015, Bangalore, India.

[8] J-O Nilsson, A.K. Gupta, and P. Handel, "Foot-mounted inertial navigation made easy," *Int. Conf. on Indoor Positioning and Indoor Navigation (IPIN)*, Busan, Korea, October 27-30, 2014.

[9] J-O. Nilsson, I, Skog, K.V.S. Hari, and P. Händel, "Foot-mounted INS for everybody – An open-source embedded implementation," *IEEE/ION Position Location and Navigation Symp. (PLANS)*, April 24-26, 2012, Myrtle Beach, South Carolina, 2012.

[10] J-O. Nilsson I. Skog, and P. Händel, "An Open-source Multi Inertial Measurement Unit (MIMU) Platform," *IEEE Int. Symp. Inertial Sensors and Systems*, Laguna Beach, California, USA, 6-7 Jan 2014.

[11] J-O, Nilsson, I. Skog, and P. Händel, "Aligning the Forces – Eliminating the Misalignments in IMU Arrays," *IEEE Trans. Instrum. Meas.*, Vol. 63, No. 10, pp. 2498-2500, Oct. 2014.

[12] W. Hu, Y. Wang, and L. Song, "Sequence-Type Fingerprinting for Indoor Localization," *Int. Conf. on Indoor Positioning and Indoor Navigation (IPIN)*, Banff, Alberta, Canada, October 13-16, 2015.

[13] V.V. Kosyanchuk, A.S. Smirnov, and A.A. Panyov, "Navigation System for a Wide Range of Tasks Based on IMU Aided with Heterogeneous Additional Information," *Int. Conf. on Indoor Positioning and Indoor Navigation (IPIN)*, Banff, Alberta, Canada, October 13-16, 2015.

[14] J-O, Nilsson, D. Zachariah, I. Skog, and P. Händel, "Cooperative localization by dual foot-mounted inertial sensors and inter-agent ranging," *EURASIP J. Adv. Sig. Pr*, Vol. 2013:164, 2013.