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Inertial Sensors Integrated with Clothing to Localize People Inside Buildings

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***Abstract*—This article presents a wearable system that localizes people in the indoor environment, using data from inertial sensors. The sensors measure the parameters of human motion, tracking the movements of the torso and foot. For this purpose, they were integrated with shirt and the shoe insole. The values of acceleration measured by the sensors are sent via Bluetooth to a smartphone. The localization algorithm implemented on the smartphone, presented here, merges data from the shirt and the shoe to track the steps made by the user and filter out the localization errors caused by movements the shirt and torso. The experimental verification of the algorithm is also presented.**

***Keywords*—inertial sensors, wearable system, step length estimation, indoor localization, localization system, intelligent T-shirt.**

I. Introduction

SYSTEMS that are using inertial sensors to localize people, are currently intensively developed in many research centers [1-5]. Such systems are used as autonomous systems [6] or as a complementary to satellite navigation in cases where the satellite signal is not available [7]. In inertial systems that localize people, accelerometers and gyroscopes are used to collect information about human motion [8]. The continuous tracking of movements allows to determine the location of the user. A lot of advanced algorithms are proposed in the literature for this purpose, which differ in computational complexity [9]. Frequently used advanced filtering algorithms (e.g. Kalman filter or particle filters) [10] require the use of relatively high computational resources in the case of real time localization. Therefore, the possibility of implementing such algorithms in wearable systems is limited because of limited energy resources available from miniature batteries. Also miniature processors that can be easily integrated with clothes have limited computing power. Therefore, in such cases, simple algorithms should be utilized to determine the location of people. Such simplified algorithms can detected the number of steps and the direction of the march [10]. To estimate the walking distance based on the number of steps, it is very important to determine the length of the step because even small differences between real and estimated value can accumulate in time and change significantly the estimate of the user's position.

The article presents a system for locating people, which uses miniature inertial sensors (accelerometers, magnetometers and gyroscopes). The sensors are integrated with a t-shirt and shoe insole, that's why it is possible to determine the user's location on the basis of speed and walking direction analysis. This system uses an algorithm, developed by the authors, that estimates the user's step length, which allowed to increase the location accuracy compared to the system that assumes a fixed length of steps [12]. The user's position is calculated by a microcontroller that is integrated with the T-shirt. Then location data are sent to the smartphone via a Bluetooth wireless link. The user's location can be stored in the cloud for further analysis and presentation.

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II. Objectives

A. System Structure

The system for people localization presented in this article, consists of a T-shirt and a shoe insole equipped with inertial sensors. The structure of the system is shown in Fig. 1. The sensors are located on both textile elements, while the microcontroller that is calculating user's position is placed on the shirt. Inertial sensors are placed on the chest and beneath the metatarsus (on the shoe insole). The current location can be sent to a smartphone. For data transmission between the electronic wearable modules, wireless transmission was applied. The design of the system modules is presented in the further part of this section.

B. T-shirt module

The T-shirt module shown in Fig. 2 consists of electronic components that measure linear and angular acceleration and process their values to estimate user's position. All electronic components were sewn into the T-shirt using electrically conductive threads that were also utilized for electrical interconnections between modules. The main element of the system is the Adafruit Flora microcontroller, which collects data from inertial sensors. The inertial module used to estimate the direction and distance of displacement is the Adafruit BNO055 consisting of 3 axes - accelerometer, magnetometer and gyroscope. The measurement data is sent to a mobile phone using the Adafruit Bluetooth Low Energy module. This system is equipped with a miniature power module that uses three small, low profile batteries with a voltage of 1.5 V. The total power consumption is 100 mW. To maintain user comfort, the miniature battery module is placed directly on the T-shirt, at the bottom part.

Fig. 2 shows the connections of the T-shirt and electronic modules that have been sewn directly into the textile material. The Adafruit Flora module (no. 1 in Fig. 2) is an AVR Atmega

32u4 microcontroller that is compatible with the Arduino environment. The Adafruit Flora controller receives data from the inertial module (number 3 in Fig. 2 and Fig. 3) and processes it to estimate the azimuth and distance travelled by the user. The estimated results of the user's position change are then sent by the Bluetooth Low Energy (LE) module to the smartphone, where the location is estimated and visualized. Location data, the direction of walk or acceleration can be transferred to a remote server for further analysis.

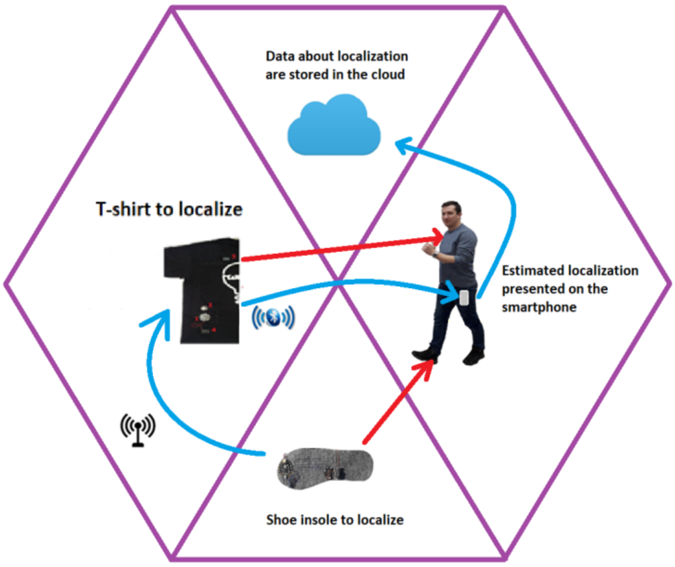

Fig. 1. Structure of system to localize people inside the buildings.

C. *Shoe insole module*

The main function of the shoe insole module, shown in Fig. 3, is to identify the step length based on the linear acceleration values. As with the T-shirt module, this module also consists of the BNO055 inertial sensor and the Adafruit controller.

Wireless communication was used to send data between the module placed in the insole and in the T-shirt. For this purpose, RFM69HCW radio modules operating in the 434 MHz band were applied. Electrical connections between the electronic parts were made using a 316L electrically conductive thread with a diameter of 0.25 mm sewn on felt material from which the insole was made. This type of connection, unlike typical copper wires, allows to maintain user comfort due to the high elasticity of the thread, which does not stiffen the insert. The sewn thread also has a much better bending strength than standard electric wires, which is important when making electrical connections on the insert module. The manufacturer indicates that the linear resistance of the thread is 30 Ω/m. In the presented insert, the length of connections between modules does not exceed 10 cm, with a maximum resistance value of 9 Ω, which does not cause errors in data transmission.

The power supply unit used in the prototype had to be replaced during tests. To simplify the experiment the battery container was connected via mini-socket by copper wires.

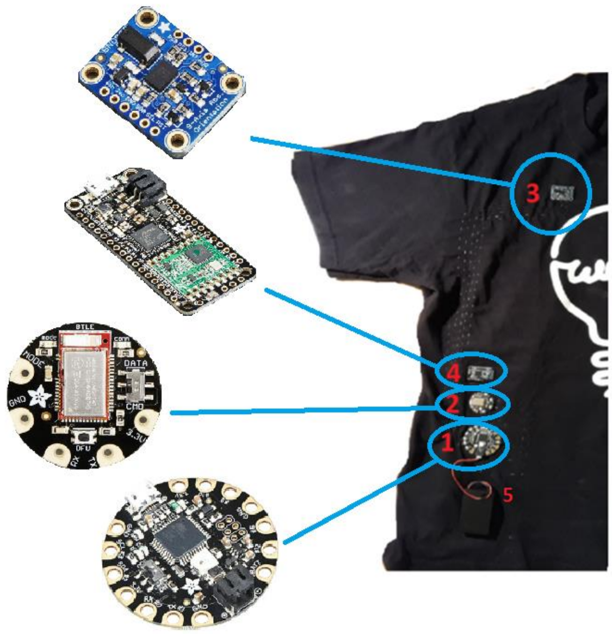

Fig. 2. Electronic T-shirt module to detect people inside the building: 1- Flora AVR microcontroller modules, 2-BT LE Bluetooth, 3- inertial module BNO055, 4–RFM69HCW radio module, 5-battery

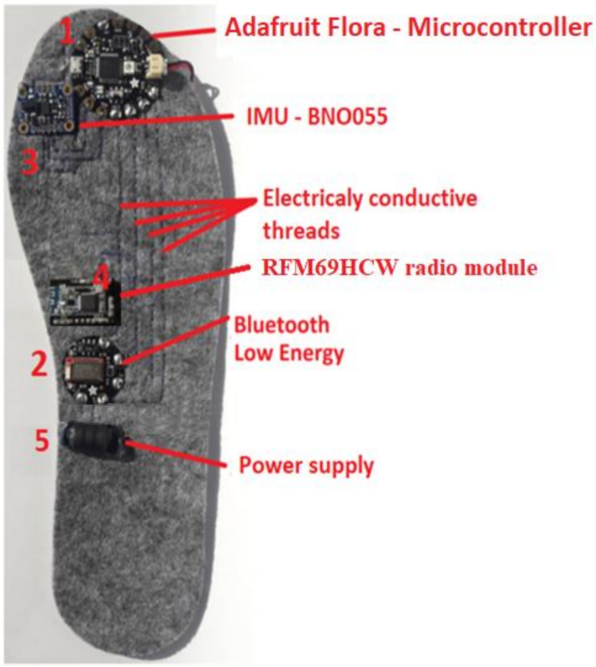

Fig. 3. Electronic insole placed in the shoe. Second module to detect people inside the building: 1-Flora AVR microcontroller modules, 2-BT LE Bluetooth module, 3- inertial module BNO055, 4 - RFM69HCW radio module

The shoe insole with electronic modules presented in Fig. 3 must be covered with a felt insert with appropriately positioned holes for the system modules before inserting into the user's footwear, so that the user does not feel discomfort caused by their presence when walking.

Fig. 4 shows the places in which the placement of electronic modules is inadvisable due to the greatest pressure forces that occur when walking in people with correct foot build without the abovementioned drawbacks [13-14].

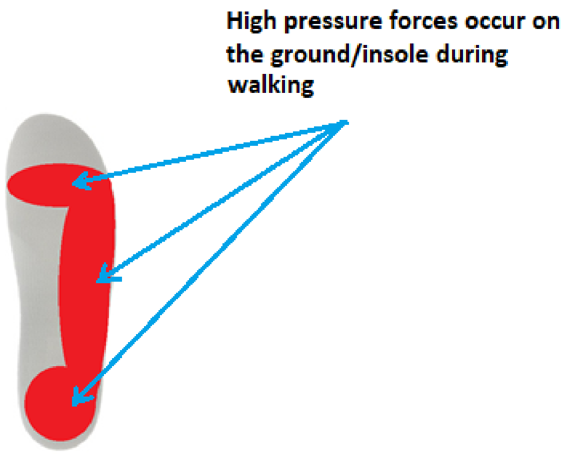

Fig. 4. Places where electronic modules should not be installed because of the high pressure forces occur during walking.

III. Methods - Localization Algorithm

The system has been designed to locate people in motion by tracking the direction of move and estimating its distance. The direction of movement is calculated using the data from sensors placed on the shirt and in the shoe. This solution was proposed to improve the accuracy of the angle detection compared to the older version of the system that was using only sensors attached to the shirt [11]. In addition, placing inertial sensors in the shoe allows to estimate the length of the step more accurately which was not possible in a system with only sensors placed in a T-shirt.

The system presented in this paper uses very simple algorithm that was proposed to minimize the power consumption for miniature power sources. The data from one axis of gyroscope was analyse for this reason. Because the vertical orientation of module on the shirt is not likely to be modified during walk, the approximation of walking angle was possible.

The BNO055 inertial modules used in this system are equipped with DMP – digital motion processors that provide information about the angle of rotation around three axes. To determine the direction of the march, a rotation angle around the vertical axis is needed. Given the placement of the sensors on the body, in the case of the T-shirt it is the y-axis, while for the insert it is the z-axis.

The former version of the algorithm that used only one accelerometer did not give satisfactory accuracy, especially when it comes to the direction of motion [10]. This was due to the detection of torsional movements of the body made during the march, which resulted in an incorrect determination of the direction of movement (azimuth angle). The combination of data from two sensors located in different parts of the body allows to significantly reduce this error by comparing the azimuth angle calculated on the basis of data from two sensors. When the difference between the azimuth angle determined using the T-shirt and insert data is less than 25°, the algorithm updates the azimuth used to estimate the location using the average of two sensors. Otherwise, the previous angle value is assumed and only the displacement length is updated.

The positioning algorithm used in the system is shown in Fig. 5. The algorithm starts when motion is detected in both sensors by exceeding the threshold value of acceleration. Step detection is based on a comparison of the resultant acceleration from the three x, y, z axes. If the value is greater than or equal to the 4 $\frac{m}{s^2}$ limit, the system identifies that the user has taken the step. This acceleration threshold was selected experimentally based on the analysis of measurement data that was recorded during testing.

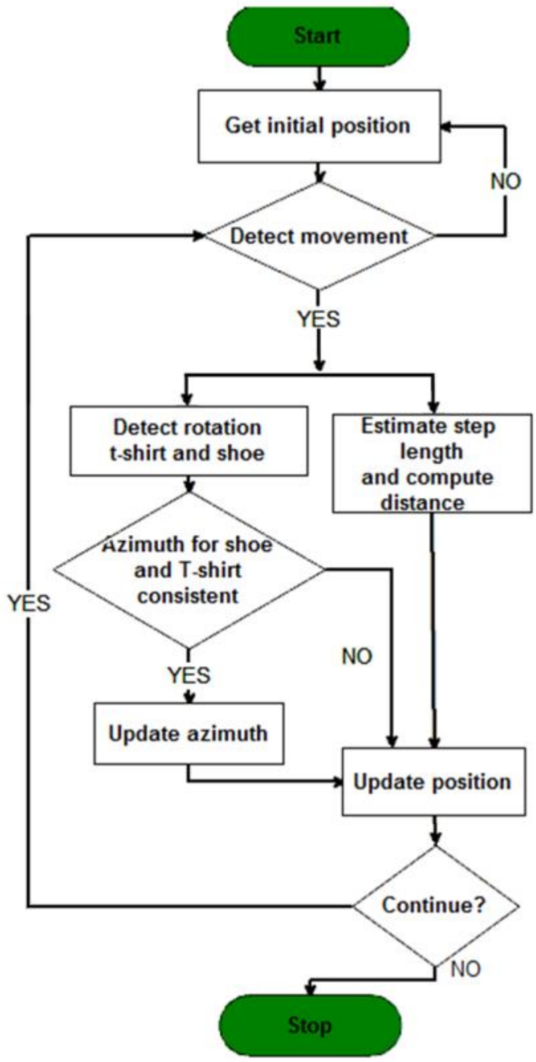

Fig. 5. Algorithm for estimating the direction of travel and distance of walk.

In the initial version of the algorithm, implemented by the authors, a fixed step length was assumed. This resulted with the limited accuracy of the algorithm in the case of a person moving with a variable speed. To improve the accuracy of the original algorithm, a step length estimation method was used.

A. Azimuth Estimation Algorithm

To determine the direction in which the user moves, the algorithm must determine the initial azimuth value. At the starting point, the azimuth angle value is computed by the magnetometer, when the user is in the initial position. If the value of the azimuth angle is e.g. 65º, algorithm calibrates the system by setting the value equal to 0º. Then the initial value is also saved for further processing. After the calibration process, the algorithm subtract the initial value (equal in this case 65º) from each newly received frame containing the angle with which the user moves. Then the algorithm quantizes the obtained angle value by bringing it closer to the appropriate zone. Each of the zones indicates the direction of movement. Fig. 6 shows the division into ranges of 45º each marked in green. There are 8 zones designated for the user's movement directions. One of the system's objectives is to average traffic direction to 8 ranges. The user can move in directions such as: north, northeast, east, southeast, south, southwest, west, northwest. Ranges have been introduced to eliminate unnecessary noise that may rise during user movement and to provide clear visualization of the route travelled.

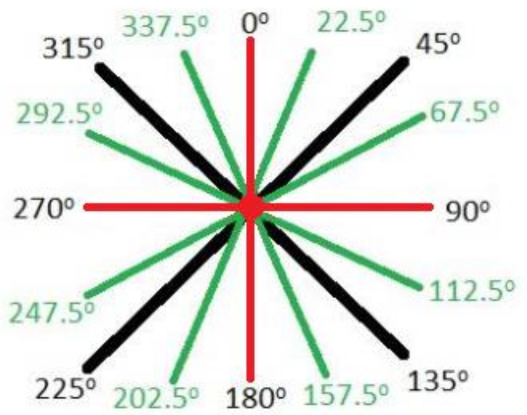

Fig. 6. Zone division of angles in the algorithm of determining the direction of motion.

The number of 8 quantized directions of traffic in which the user can move is marked in red and black. If the azimuth value during the user's movement is in the range of 67.5º to 112.5º (marked in green on the chart), we estimate that the user is moving eastwards.

B. Step Length Estimation Algorithm

The algorithm used to determine the step length retrieves data on linear acceleration from a three-axis accelerometer located in the shoe insole. Acceleration values measured for the x, y and z axes are used to determine the resultant acceleration values. During preliminary experiments, it was observed that increasing the step length increases the maximum value of the resultant acceleration measured by the sensors.

The step length considered here was identified in our experiment for a male of 180 cm height, walking with typical velocity for building interior that is around 1 m/s. For this potential user of the system, the correlation between resultant acceleration and the step length was successfully used. The significant changes of the dynamic of walk would result with different values resultant acceleration but it would take place only if the speed of walk would be either very small or very high for the person of considered height. Having user of different height that would make steps of different length, the new characteristic values of resultant acceleration should be identified.

The step length detection algorithm developed by the authors analyses 4 values of the resultant acceleration per second. Estimation of the step length occurs after collecting the first 100 values, therefore it is initially assumed that the step length value is the user's average step length, i.e. 70 cm. The algorithm estimates the step length equal to 80 cm when for the last hundred samples the resultant acceleration value will be greater than or equal to 17 $\frac{m}{s^2}$. If this value is less than 17 $\frac{m}{s^2}$ but greater than or equal to 7 $\frac{m}{s^2}$, it is assumed that the step length is 60 cm, while for the range from 7 $\frac{m}{s^2}$ to 4 $\frac{m}{s^2}$ it is 40 cm.

IV. RESULTS

In order to compare the performance of the localization algorithm with step length detection and constant step length, tests were carried out to determine the distance travelled by a human subject in a 25 m x 8 m room. The tests were carried out in one room within one floor. In the algorithm based on a fixed step length, it was assumed that the steps are 70 cm each. The results of the approximated walking distance are shown in Fig. 7. The test scenario included a 19-meter walk made by the user in a straight line. One dot on the line in Fig. 7 means double step. The green line is the reference path where the start point is 0 m and the end point is 19 m. The algorithm with a fixed step length (70 cm) indicated that the user had completed 32 steps. In this case, the value estimated on the basis of the algorithm was 70 cm x 32 steps = 2240 cm (orange line in Fig. 7). The distance estimation error was 340 cm. The walking path calculated using the step length estimation method is marked in red. The algorithm indicated that the user took 8 steps with a length of 70 cm and 24 steps with a length of 60 cm. 8 steps x 70 cm + 24 steps x 60 cm = 2000 cm (red data series). The distance estimation error was 100 cm, i.e. 240 cm less than the fixed step length algorithm.

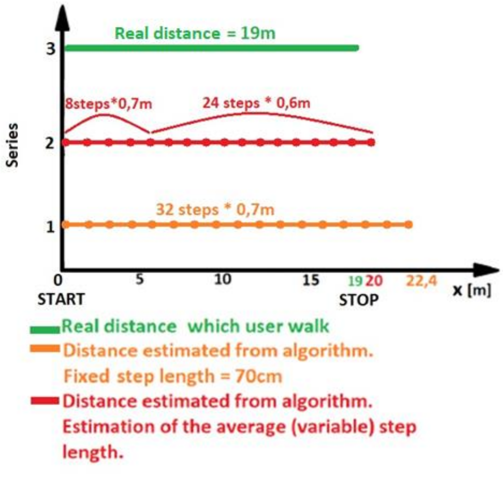

Fig. 7. Results of the length estimation during the march.

TABLE I
LOCALIZATION ERROR

No	Human location [m]	[PART1] Localization via only insole module [m]	[PART2] Localization with using T-shirt and insole modules [m]	Localization Error - version 1 [m]	Localization Error – version 2[m]
1	x=0; y=0	x=0; y=0	x=0; y=0	0	0
2	x=-2; y=2	x=-2; y=2	x=-2; y=2	0	0
3	x=-15; y=2	x=-12; y=2	x=-12; y=2	3	3
4	x=-15; y=2,5	x=-12; y=2,5	x=-12; y=2,5	3	3
5	x=-12; y=2,5	x=-11; y=2,5	x=-11; y=2,5	1	1
6	x=-10; y=8	x=-9; y=7	x=-9; y=7	1,4	1,4
7	x=-6; y=2,5	x=-6; y=5,5	x=-6; y=4,5	3	2
8	x=-2,5; y=2,5	x=-2,5; y=7	x=-2; y=4,5	4,5	2,1
9	x=-3,5; y=5	x=-4,5; y=10	x=-3,5; y=7	5,1	2
10	x=-2,5; y=2,5	x=-2,5; y=7	x=-2, y=4,5	4,5	2,1
11	x=4,5; y=2,5	x=3; y=8,5	x=4,5; y=4	4,5	1,5
12	x= -15; y=4	x= -13 ; y=8	x= -13 ; y=4	4,5	2

Fig. 8 shows the results of the experimental verification of the localization system. Tests were carried out inside the building, where the user could move within a 20 m x 20 m room. The path that the volunteer followed, was marked with a black line. The starting point, which was known a priori, was marked in red. This assumption was adopted because there is only one entrance to the room, and in is assumed that in the future RFID tags will be used to provide information about crossing the entrance point. The algorithm assumes that the user cannot leave the area of the room where the test is carried out. The results marked with green line in Fig. 8 were obtained for the algorithm that was using the sensors located on the T-shirt and in the insert. The blue line marks the location estimation results obtained with an algorithm using only one sensor in the insole. In the case of an algorithm using 2 sensors, the maximum location error calculated as the largest distance between the determined and actual position was 2 m. In the case of an algorithm using 1 sensor, the maximum error was around 5 m.

Table 1 presents the location error, which was calculated for two localization methods. This table shows in another way the data from experiment whose results are shown in Fig. 8. The location error was calculated for 12 check-points by comparing the difference of x and y coordinate given by the algorithms and their actual coordinates. The points in table 1 that are corresponding to the points on the traces presented in fig. 8 have been marked with the numbers. The check-points have been arbitrarily chosen for some specific places inside the room were objects (furniture and laboratory equipment) where located. During the walk the person needs to change the direction at the proximity of those points to avoid the collision with obstacles. It is then the place where the greatest changes in acceleration appear and this may result with increase of localization error. The localization error was calculated for two versions of the algorithm: with the accelerometer on the insole (version 1) and the hybrid localization algorithm which uses accelerometers on t-shirt and insole (version 2).

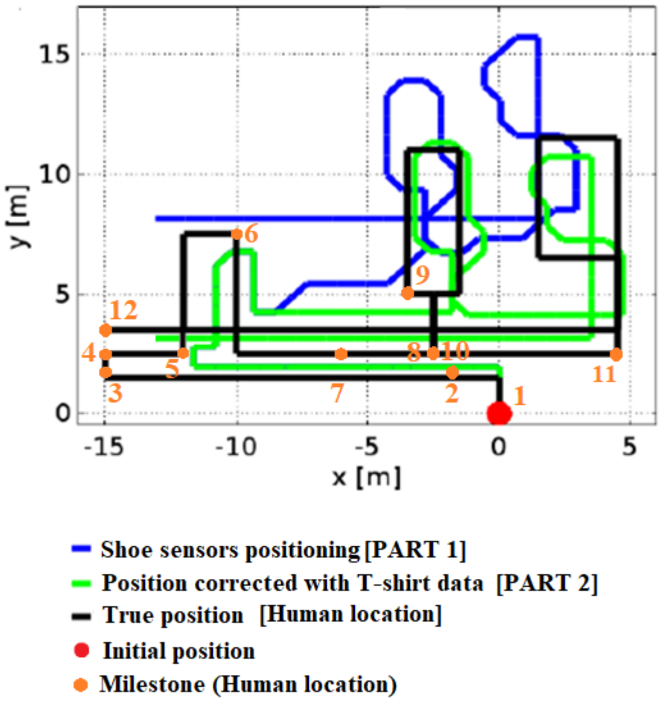

Fig. 8. Results of tests carried out on the positioning algorithm.

The results gathered in Table 1 show that localization error obtained from hybrid system (version 2) is smaller than the error in the first version of the system. For the case of the first check-point, when the user has not yet taken any steps the localization error equals 0 m. During the walk the localization error between 2nd and 6th check-point is similar for both versions of algorithms. It is noticeable that between the check-point number 8 and 12, the value of error in the hybrid method (version 2) is much smaller than for single-sensor based algorithm (version 1). For the last check-point nr. 12 the localization error equals 4.5 m in version 1 and 2 m version 2 of the system. This table present that the hybrid method is more accurate for localization of people walking inside the building.

V. CONCLUSIONS

The paper presents the system that was designed to localize people using clothes-embedded wearable inertial sensors. The proposed system uses data from 2 wearable sensors sewn directly into clothing. One of the sensors was placed near the chest and the other near the foot. This solution significantly reduced the impact of the torso turns on the location result when walking, compared to the formerly developed algorithm that utilized only one sensor.

The system utilizes the wearable sensors that have to be located in the proximity of the body. To keep comfort of a the system's user, the miniaturized electronic modules designed to be integrated with clothes were used. Electrical interconnections between the modules were made with conductive threads. It was shown that this technology is suitable for short-distance connections that were able to transmit data as well as connect the supply voltage to the modules. The small thickness (c.a. 0.5 mm) and high flexibility of such threads has no negative impact on the users comfort.

Further research on the designed system will cover the analysis of the bending endurance of the textile connections as well as the design of equipment maintenance procedure. This is particularly important in the case of a wearable system that is integrated with clothes which has to be washed.

The step length estimation algorithm that was presented in this article improved the location accuracy. In the case when user changes the speed of walk, this can have a great impact on the accuracy of localization in the systems where the distance error can accumulate (e.g. dead reckoning). The distance estimation error was reduced from 18% to 5% at the reference distance of 19 m.

The analysis of the experimental results obtained with the system presented here shows that the use of two independent inertial sensors can improve the location accuracy. The proposed algorithm is less sensitive to the torsion of the body that may affect the detection of walking direction. The improved detection of walking direction together with adaptive approximation of the step length allowed reducing the position error compared to the algorithm based on a single sensor. The maximum positioning error obtained with the improved algorithm in the room of area equal to 400 m^2 has been reduced to 3 m.

In the current version of the system, the initial position is assumed a priori. As a part of further work, it is planned to implement automatic detection of people entering the room using RFID nodes.

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