The GETA Sandals: A Footprint Location Tracking System

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Abstract. This paper presents the design, implementation, and evaluation of a footprint-based indoor location system on traditional Japanese GETA sandals. Our footprint location system can significantly reduce the amount of infrastructure required in the deployed environment. In its simplest form, a user simply has to put on the GETA sandals to track his/her locations without any setup or calibration efforts. This makes our footprint method easy for everywhere deployment. The footprint location system is based on the dead-reckoning method. It works by measuring and tracking the displacement vectors along a trial of footprints (each displacement vector is formed by drawing a line between each pair of footprints). The position of a user can be calculated by summing up the current and all previous displacement vectors. Additional benefits of the footprint based method are that it does not have problems found in existing indoor location systems, such as obstacles, multi-path effects, signal noises, signal interferences, and dead spots. However, the footprint based method has a problem of accumulative error over distance traveled. To address this issue, it is combined with a light RFID infrastructure to correct its positioning error over some long distance traveled.

1 Introduction

Physical locations of people and objects have been one of the most widely used context information in context-aware applications. To enable such location-aware applications in the indoor environment, many indoor location systems have been proposed in the past decade, such as Active Badge [1], Active Bat [2], Cricket [3], smart floor [4], RADAR [5], and Ekahau [6]. However, we have seen very limited market success of these indoor location systems outside of academic and industrial research labs. We believe that the main obstacle that prevents their widespread adoption is that they require certain level of *system infrastructural support* (including hardware, installation, calibration, maintenance, etc.) inside the deployed environments. For example, Active Badge [1], Active Bat [2], and Cricket location systems [3] require the installation of infrared/ultrasonic transmitters (or receivers) at fixed locations (e.g., ceilings or high walls) in the environments. In order to attain high location accuracy and good coverage, the system infrastructure requires large number of transmitters (or

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receivers) installed in the deployed environments. This is beyond the reach of ordinary people to afford, operate, and maintain the infrastructure. WiFi based location systems such as RADAR [5] and Ekahau [6] require an existing WiFi network in the deployed environment. For example, the Ekahau location system recommends a WiFi client to be able to receive signals from 3~4 WiFi access points in order to attain the specified location accuracy of 3 meters. This high density of access points is unlikely in our everyday home and small office environments. In addition, most WiFi based location systems require users' calibration efforts to construct a radio map by taking measurements of WiFi signal strength at various points in the environment. This forms another barrier for users. Smart floor [4] can track the location of a user by using pressure or presence sensors underneath the floor tiles to detect the user's gait. This infrastructure cost is expensive because it requires custom-made floor tiles and flooring re-construction.

Significantly reducing the needed system infrastructure serves as our main motivation to design and prototype a new *footprint location system* on traditional Japanese GETA (pronounced "gue-ta") sandals. This footprint location system can compute a user's physical location solely by using sensors installed on the GETA sandals. To enable location tracking, a user simply has to wear the GETA sandals with no extra user setup & calibration effort. This system works by attaching location sensors, including two ultrasonic-infrared-combo readers and one ultrasonic-infrared-combo transmitter, on the GETA sandals. The basic idea can be described by looking at a person walking from location A to location B on a beach. He/she will leave a trial of footprints. To track a person's physical location, the system continuously measures a *displacement vector* formed between two advancing footprints (advancing in the temporal sense). To track a user's current location relative to a starting point, the system simply sums up all previous *footprint displacement vectors* leading to his/her current footprint location. This idea is similar to the so-called (deduced) *dead-reckoning navigation* dated back to the medieval time when the sailor/navigator would locate himself/herself by measuring the course and distance sailed from a starting point. In our system, this dead reckoning idea is adapted in tracking human footprints. We believe that having a *wearable location tracker* is an important advantage in our footprint location system over infrastructure-based indoor location systems. Users simply need to wear our GETA-like shoes, and our location system can work anywhere they want to go.

In addition to the benefit of low infrastructure cost, the *footprint location system does not have problems commonly found in existing indoor location systems*. For example, existing wireless based solutions (e.g., using radio, ultrasonic, or infrared) can experience poor position accuracy when encountering obstacles between transmitters and receivers, multi-path effects, signal noises, signal interferences, and dead spots. On the other hand, our footprint location system avoids almost all of these problems. The reason is that the location sensors (ultrasonic-infrared transmitters and readers) in our footprint method only need to cover a small sensing range, which is the short distance between two sandals in a maximum length of a walking step (< 1.5 meters). Assume walking on a relatively smooth surface, the footprint location sensors are unlikely to encounter any obstacles or experience multi-path effects, signal noises, and signal interferences over this small sensing range. This is in contrast to existing wireless (radio, ultrasonic, or infrared) based location systems where the sensing range must be large enough to cover the distance between fixed location sensors in the environment and a mobile location sensor on a user. This short sensing range in our footprint method also brings two additional advantages: (1) location sensors can significantly reduce its power consumption due to short sensing range, and (2) location sensors (ultrasonic-infrared) have high accuracy under such short sensing range (e.g., 0.2 *mm* in static setting).

There is one important shortcoming in our footprint location system called the *error accumulation* problem. It is inevitable that a small amount of error is introduced each time we take measurements to calculate a displacement vector. Consider a user has walked n steps away from a starting point. His/her current location is calculated as a sum of these n displacement vectors. This means that the current location error is also the sum of all errors from these n previous displacement vectors. In other words, the error in the current footprint measurement will be a percentage of the total distance traveled. To address this error accumulation problem, we utilize a small number of passive RFID tags with known location coordinates in the environment. A small RFID reader is also placed under a GETA sandal to read these RFID tags. When a user walks on top of a location-aware RFID tag, the known location coordinate of that RFID tag is used instead of the calculated footprint location. Encountering a RFID tag has the same effect as resetting the accumulated error to zero. Although these location-aware RFID tags are considered system infrastructure, they constitute very light infrastructure because (1) RFID tags are relatively inexpensive in cost (< $1 each) and easy to install, and (2) only a very small number of RFID tags are needed. Based on our measurements in Section 4, the average error per footstep is only about 4.6*mm*. If we want to limit the average error to 46*cm*, we only need to install enough RFID tags in the environment such that a user is likely to walk over a RFID tag approximately every 100 steps.

There are several pervious systems that are also based on incremental motion and dead reckoning. Lee et al [11] proposed a method to estimate the user's current location by recognizing a sequence of incremental motions (e.g., 2 steps north followed by 40 steps east, etc.) from wearable sensors such as accelerometers, digital compass, etc. Lee's proposed method differs from our footprint tracking system in that it can only recognize a few selected locations (e.g., bathroom, toilet, etc.) rather than track location coordinates. Point research [12] provides a vehicle self-tracking system that provides high location accuracy by combining the dead-reckoning method (wheel motions) and GPS. The solution from Point research differs from our method which is based on footprint tracking in normal human walking motion rather than mechanical wheel movements.

At the time of this paper writing, we have gone through three design-and-evaluation iterations. Rather than presenting only the last (3rd) design and evaluation, we think that readers may also be interested to know these intermediate designs as well as mistakes we made on them. The remainder of this paper is organized as follows. In Sections 2 to 4, we describe our three design-and-evaluation iterations, including performance evaluations and discussions about design mistakes. Section 5 draws our summary and future work.

2 Initial Design: Design Version I

The human walking motion can be modeled by stance-phase kinematics shown in Fig. 1. A forwarding walking motion is consisted of a sequence of three stances – *heel-strike*, *mid-stance*, and *toe-off*. In the heel-strike stance, the body weight pushes down from the upper body to the lower body, resulting in both feet in firm contact with the ground. This generates a footprint on the ground. In the mid-stance, the body raises one (left) foot forward and above the ground. In the toe-off stance, the body weight again pushes down on the forwarded (left) foot, again resulting in both feet in contact with the ground. This creates another footprint on the ground.

The basic idea behind our footprint location tracking system is to (1) detect heel-strike and toe-off stances, and then (2) take measurement of two feet's *displacement vector* v_d (i.e., the footprint vector) on the ground. As shown in Fig. 2, given a starting point in a location tracking region (x_{start}, y_{start}), e.g., the entrance of home or a building, we can compute the current position of a user, who has walked n number of steps away from the starting point, by summing up all displacement vectors Σv_{di}, for $i=1..n$, corresponding to these n footsteps.

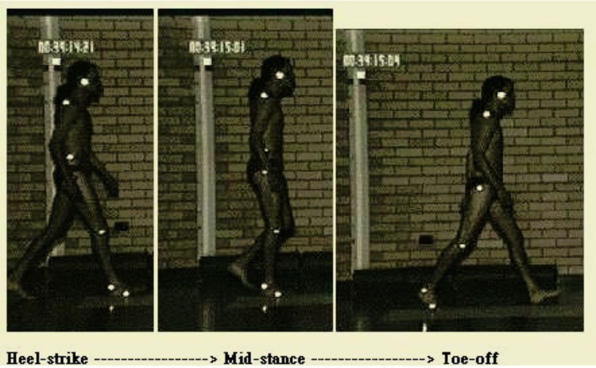

Fig. 1. Three stances in a normal human walking motion

2.1 Footprint Positioning Algorithm

To measure the displacement vector v_d for each footprint, we place two ultrasonic-infrared-combo receivers on the left sandal and two ultrasonic-infrared-combo transmitters on right sandal shown in Fig. 3. The components for ultrasonic-infrared transmitters and receivers are obtained by disassembling the NAVInote's [8] electronic pen and base unit. In order to make both the receivers and transmitters face

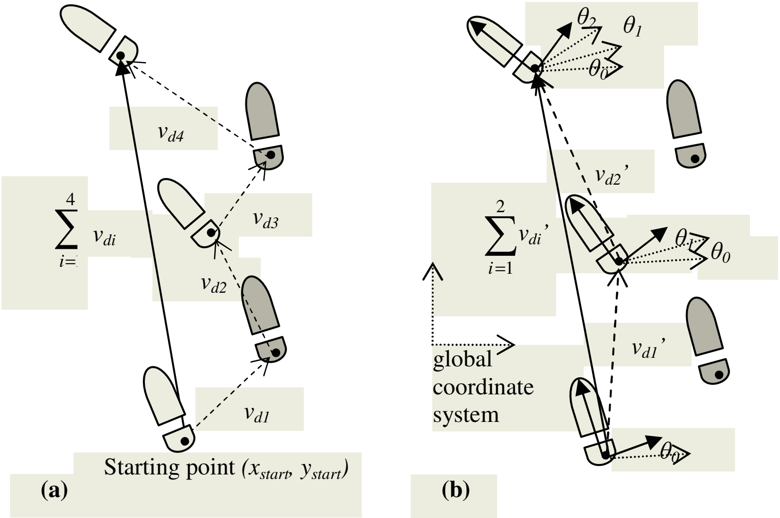

Fig. 2. The user has walked four footsteps 1-4. Fig. 2(a) shows these displacement vectors (v_{di}) corresponding to these displacement vectors. Fig. 2(b) shows θ_i as the rotational angel between the current local coordinate system and the previous local coordinate system in the previous footstep

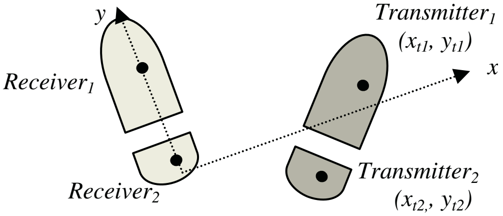

Fig. 3. It shows the locations of ultrasonic-infrared receivers and transmitters on the sandals. The coordinates of the transmitters on the right sandal is relative to the local coordinate system on the left sandal

directly toward each other during normal walking motion[1], they are placed on the inner sides of the sandals. The prototype of the GETA sandals is shown in Fig. 7. Through NAVInote APIs, we obtain the (x, y) coordinates of these two transmitters located on the right sandal. Denote them as (x_{t1}, y_{t1}) and (x_{t2}, y_{t2}) as shown in Fig. 3. Note that the ultrasonic-infrared-combo technology can achieve very fine position accuracy and resolution at the short sensing range between two sandals. Under static setting, the measured average positioning error is $< 0.2mm$ and the resolution is $< 0.2mm$.

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[1] We assume that people don't intentionally walk cross-legged.

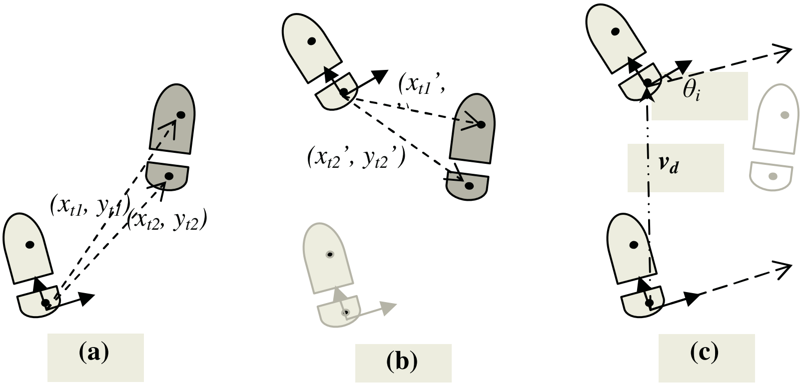

Fig. 4. Before moving the left foot, the coordinates of the transmitters on the right sandal, (x_{t1}, y_{t1}) and (x_{t2}, y_{t2}), are recorded as shown in (a). After walking the left foot, (x_{t1}', y_{t1}') and (x_{t2}', y_{t2}') are recorded as shown in (b). To calculate v_d, we have to consider the rotation angel θ_i, translate *(dx, dy)* to the coordinate system of the left foot, and then transform them into the global coordinate system to get the displacement vector v_d, as shown in (c)

The coordinates of these two transmitters are measured relative to the *local coordinate system* of the left sandal, where the origin of this local coordinate system is at the heel position and the *y-axis* forms a straight line from the heel to the toes. Since moving left foot also changes the local coordinate system, it is necessary to *re-orientate* the displacement vector from its local coordinate system to a global coordinate system. The global coordinate system is set to be the coordinate of the starting point. To perform this orientation translation, we need to compute the *orientation angle* θ of local coordinate system relative to the global coordinate system.

Denote the current step as the *i*-th left footstep. The orientation angle θ can be calculated as $\Sigma\ \theta_i$, where θ_i is the rotational angle between the *i*-th left footstep's coordinate system and the *(i-1)*-th left footstep's coordinate system. This means that to compute the orientation angle θ, we need to compute θ_i for each new left footstep as illustrated in Fig. 2(b).

Fig. 4 shows (x_{t1}, y_{t1}) and (x_{t2}, y_{t2}) as the recorded coordinates of two transmitters on the right foot before moving the left foot, and (x_{t1}', y_{t1}') and (x_{t2}', y_{t2}') as their recorded coordinates after moving the left foot. As the left foot moves, the coordinate system on the left foot rotates θ_i and then translates into *(dx, dy)*. This gives us the following four sets of equations, which are sufficient to solve for three unknowns: θ_i and *(dx, dy)*.

$$\begin{bmatrix} \cos\theta_i & \sin\theta_i \\ -\sin\theta_i & \cos\theta_i \end{bmatrix} \begin{bmatrix} x_{t1} \\ y_{t1} \end{bmatrix} - \begin{bmatrix} dx \\ dy \end{bmatrix} = \begin{bmatrix} x_{t1}' \\ y_{t1}' \end{bmatrix} \qquad \begin{matrix} (1) \\ (2) \end{matrix}$$

$$\begin{bmatrix} \cos\theta_i & \sin\theta_i \\ -\sin\theta_i & \cos\theta_i \end{bmatrix} \begin{bmatrix} x_{t2} \\ y_{t2} \end{bmatrix} - \begin{bmatrix} dx \\ dy \end{bmatrix} = \begin{bmatrix} x_{t2}' \\ y_{t2}' \end{bmatrix} \qquad \begin{matrix} (3) \\ (4) \end{matrix}$$

We can then compute v_d using summed θ, dx, and dy.

$$\begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} dx \\ dy \end{bmatrix} = v_d$$

Some readers might wonder why we use two transmitters instead of one transmitter. The reason is that one transmitter only gives two equations, which are insufficient to solve three unknowns. With the additional transmitter, it can give two additional equations needed to solve three unknowns.

Prior to the above-mentioned geometry calculation, we need to detect the heel-strike and toe-off stances to measure (x_{t1}, y_{t1}) and (x_{t2}, y_{t2}). We call these two stances the *steady state* because when both feet are in contact with the ground, the measured coordinates on two transmitters are *stable* (do not change much) for some small period of time. When we detect the steady state, we record the coordinates of two transmitters and then calculate the displacement vector.

Assume that the user moves the right foot and the left foot in an interleaving manner. We can track the position of the left foot by first computing two displacement vectors from left footprint to the right footprint and right footprint back to the left footprint.

2.2 Performance Evaluation

We have evaluated the performance of our initial design. The results have shown poor positioning accuracy. The main cause of poor accuracy is due to the interference of the signals from the two transmitters. Since the receivers can not distinguish two distinct signals from two transmitters, it can calculate incorrect coordinates on two transmitters. This leads to miss-detection of the steady state and incorrect calculation on the displacement vectors. Although we tried to filter out these incorrect coordinates, our results still showed high 49% rate of steady state miss-detections. When a miss-detection occurs, dx, dy, θ, and displacement vector will also be calculated incorrectly. This leads to rapid error accumulation. Note that even a small error in the rotation angle θ, which is used to re-orient the displacement vector, can significantly reduce the position accuracy.

An additional problem is that we have not found a working method to distinguish if a person is moving forward or backward and which (left or right) foot is moving. This problem can be explained as follows. Consider the 1st case that a person is moving forward: if the right foot is moving forward, the x-coordinates of both transmitters will increase; on the other hand, if the left foot is moving forward, the x-coordinates of both transmitters will decrease. Consider the 2nd case that a person is moving backward, the situation is reverse, i.e., the x-coordinate will decrease(increase) when right(left) foot is moving backward. Given increasing x-coordinates on transmitters, it can be either right foot moving forward or the left foot moving backward. As a result, it is impossible to distinguish if a person is moving forward/background & left/right (foot movement).

3 Revised Design: Design Version II

Design II tries to fix the following three problems from design I: (1) interferences from two transmitters, (2) incorrect detections of heel-strike and toe-off stances, and (3) indetermination of forward/backward & left/right movements. Design II solves these problems by incorporating additional sensors into the GETA sandals. To accurately detect the heel-strike and toe-off stances, we have added two pressure sensors at the bottom of both sandals to sense when both feet are in contact with the ground. These pressure sensors are also used to distinguish the forward/backward & left/right movements. To eliminate interferences from two transmitters, we remove one transmitter from the right sandal and incorporated an orientation sensor by InterSense InterTrax2[9] on the front of left sandal. Fig. 7 shows the GETA sandal prototype of the revised design (version II).

3.1 Revised Footprint Positioning Algorithm

Since the orientation sensor can provide θ value for the global coordinate system, it removes one unknown in our calculation. This leads to a simpler algorithm than in version I. By measuring (x_t, y_t) and θ at the time of the heal-strike and toe-off stances, the displacement vector in the current footstep can be calculated by performing a simple rotational transformation. The displacement vector to the starting point is the sum of all the displacement vectors corresponding to the all previous footsteps.

3.2 Performance Evaluation

Fig. 5 shows the measured positioning error over different traveling distances and walking speeds. It has shown that two problems in design I have been addressed. The positioning accuracy is very good at short walking distances: the average error after walking a little more than $5m$ is only $0.36m$, or approximately 6.8%. It also shows that our new design can accurately detect the heel-strike & toe-off stands, and then take measurements to compute the displacement vector. It can be seen that the error increases only slightly with increasing walking speed. However, we can clearly observe the problem of *error accumulation* in our footprint-only method, as the positioning error increases *super-linearly* with increasing walking distance.

The error is contributed from two main sources: (1) the displacement error vector from the ultrasonic-infrared-combo device, and (2) the orientation error from the orientation sensor. The displacement error is relatively small and stable due to the high accuracy in the ultrasonic-infrared-combo device. However, the displacement error is *accumulative* in future location calculation, so the error distance follows a linear growth pattern. Note that orientation error is more destructive than displacement error, i.e., even a one-time orientation error can make the positioning error grow linearly over walking distance. This can be explained by looking at Fig. 6. After the one-time orientation error of θ_{error} occurs, the calculated path will forever deviate from the real path, leading to linear grow in error displacement. In addition, we have found that our orientation sensor becomes inaccurate after rotating over 90 degrees. In order to get more accurate rotation angle θ, we reset the orientation sensor after each left step, and then sum up each rotation θ_i to get the orientation θ. Due to this extra calculation, the orientation error of θ_i also becomes accumulative.

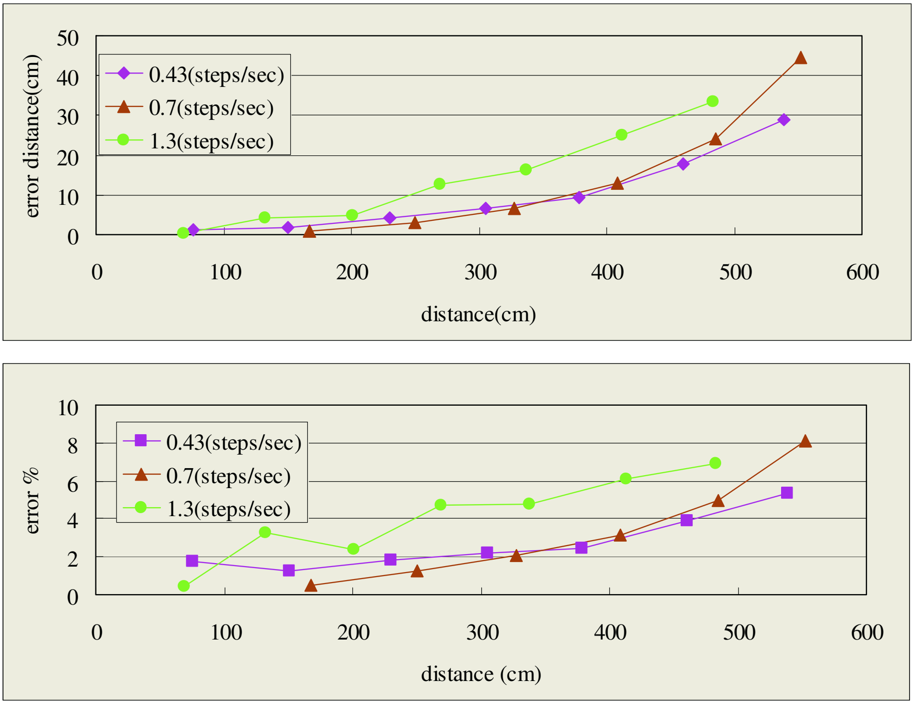

Fig. 5. The positioning accuracy (error) under different walking speeds over the walking distance

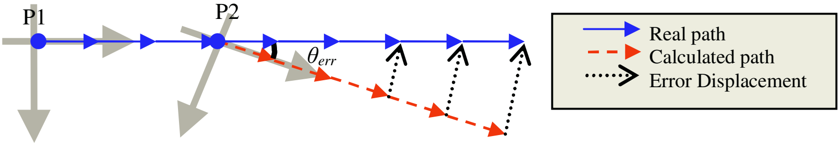

Fig. 6. Illustration of the accumulation of the error of

4 Final Design: Design Version III

Design III tries to fix the error accumulation problems in design II. Design III incorporates location-aware passive RFID tags & readers that can reset the accumulated error whenever the user steps on top of a RFID tag with a pre-determined location coordinate. These location-aware passive RFID tags forms a passive RFID grid that can be used to bound the accumulated error in design II. Since a higher RFID grid density means higher probability that a user will step on top of a passive RFID tag (therefore resetting the positioning error), the ideal density of the RFID grid can be chosen to achieve the needed positioning accuracy in the deployed environment.

The RFID solution has two parts: (1) a Skyetek M1[10] RFID reader is installed at the bottom of the left sandal, and (2) a set of passive RFID tags with the read range of 4.5 *cm* are placed in the grid fashion. We only attach one additional RFID reader to the left sandal, and the other device configuration is the same as in design II (Fig. 7.).

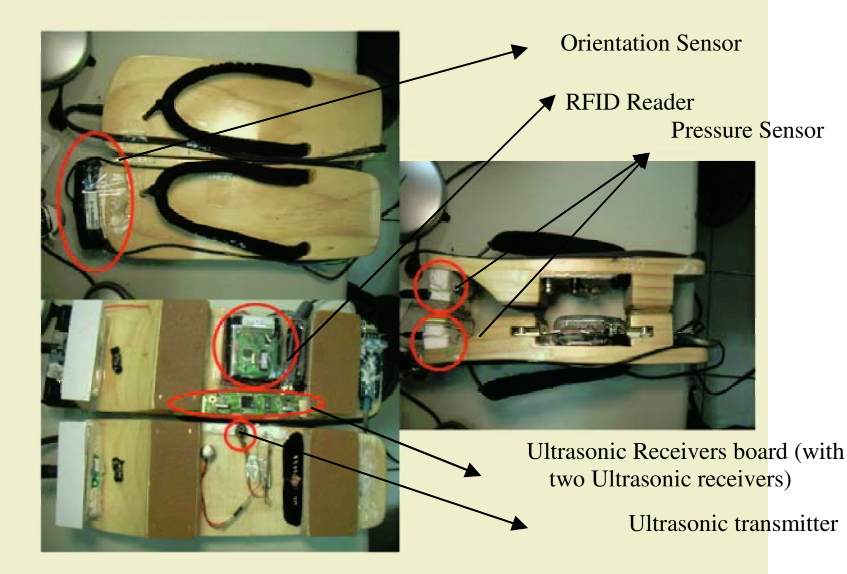

Fig. 7. It shows the prototype of final design (version III) of the GETA sandals. Prototype of design (version II) does not have the RFID reader. Prototype of design (version I) does not have the orientation sensor but has an additional transmitter

In the target environment, a server is used to maintain the table mappings between RFID tag IDs and corresponding location coordinates. When a user enters the target environment, the GETA sandal downloads its mapping table. The positioning algorithm is revised as follows. When the GETA sandal steps on top of a RFID tag, it looks up the cached mapping table to find the location coordinate of this RFID tag. Then, the current location of the user is set to the location coordinate of this RFID tag rather than from the footprint tracking method.

4.1 Performance Evaluation

We have evaluated the performance of GETA sandal (version III) in a 15x15 square meters testing environment. We have two different configurations of passive RFID grids. The first configuration places one tag every 3*m*, and the second configuration places one tag every 5*m*. Fig. 8 shows the measured positioning error over walking distance for these two configurations. The error is reset to zero when a user steps on top of a RFID tag. Fig. 8 also shows that under a random walk, there is a probability that a user may not step on a RFID tag every 3*m* or 5*m*. As a result, the errors continue to accumulate past 3*m* or 5*m* until a user eventually steps over a RFID tag.

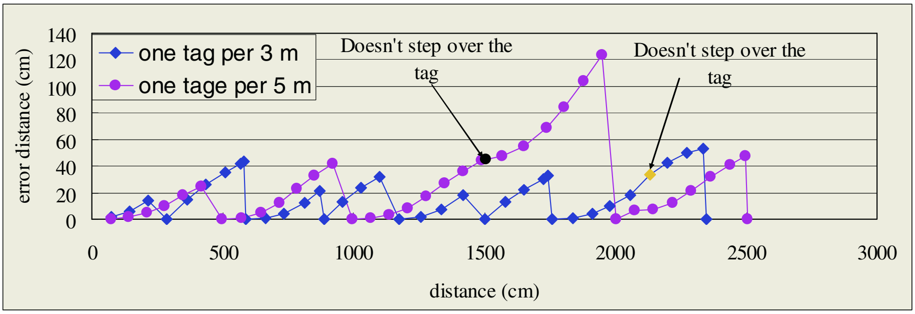

Fig. 8. The positioning accuracy (error) under different walking speeds over the walking distance

5 Conclusion and Future Work

This paper describes the design, implementation, and evaluation of our footprint-based indoor location system on traditional Japanese GETA sandals. Our footprint location system can significantly reduce the amount of infrastructure needed in the deployed indoor environments. In its simplest form, the footprint location system is contained within the mobile GETA sandals, making it easy for everywhere deployment. The user simply has to wear the GETA sandals to enable his/her location tracking with no efforts in calibration and setup. In addition to the benefit of being low infrastructure cost, the footprint based method does not have problems in infrastructure-based indoor location systems such as noises, obstacles, interferences, and dead spots. Although the footprint based method can achieve high accuracy per moving footstep, it has a problem that positioning error can be accumulated over distance traveled. As a result, it may need to be combined with a light RFID infrastructure to correct its positioning error over some long distance traveled.

There are two yet-to-be-addressed problems in our current prototype of GETA sandals: wear-ability, RFID tag placement, and stair climbing. The current wear-ability is unsatisfactory due to interconnecting all sensor components to a Notebook PC through hardwiring. In our next prototype, we would like to replace all hardwiring with wireless networking (e.g., Bluetooth), and replace processing on the Notebook with a small embedded processor. To further reduce the RFID infrastructure, we are interested to locate strategic frequently visited spots in an environment and to place these RFID tags. Stair climbing is a serious problem because the stair becomes the obstacle blocking the sensors between two sandals. To address this problem, we use the strategy of putting RFID tags at the entrances of the stairs. We can treat a stair as a transition path from one floor space to another. Then we can use the RFID to know when we move into or out a stair and change the position to the new floor space.

Acknowledgements

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