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User-installable Indoor Positioning System Using a Wi-Fi Beacon and PDR Module

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Abstract: This paper describes a user-installable indoor positioning system based on a new wireless beaconing method called a Wi-Fi location beacon, and a pedestrian dead reckoning (PDR) module. In the proposed system, the new wireless beaconing method offers an accurate positioning system using a high-gain beam antenna in the 5 GHz Wi-Fi band. The antenna forms a narrow hotspot of received signal strength (RSSI) in the space immediately below itself; the user devices detect the hotspot by monitoring the RSSI. The beaconing module is also resistant to jamming by other wireless systems and noise. Experimental results show that the proposed system can work in a high density Wi-Fi environment with over 100 Wi-Fi stations, and the positioning error of the proposed system at CDF = 90% is about 3.5 m. The positioning accuracy of the proposed system is slightly inferior to previous systems based on the Wi-Fi fingerprint method, but it achieves a similar function using a user-installable system which is easier to install and maintain than previous systems.

Keywords: indoor positioning system, Wi-Fi location beacon, PDR

1. Introduction

Smart mobility services are expected to play an important role in future life [1]. Personal mobility and human location information are especially important for attaining these smart mobility services [2]. In outdoor environments, positioning systems based on Global Navigation Satellite Systems (GNSS) are available for personal positioning [3]. However, in indoor environments, even though many indoor positioning techniques were considered in the last decade, there are no dominant techniques in widespread use. The reason may be that most indoor positioning techniques cannot provide both sufficient accuracy and continuously updated location information (see **Table 1**).

Here, the "Type of the Location info." indicates whether the location information is continuous or discrete.

Therefore, systems which combine the Wi-Fi fingerprint technique and PDR have been studied for indoor positioning [15]. Here, the authors describe a basic Wi-Fi fingerprint technique.

Table 1 Earlier indoor positioning techniques.

Technique	Accuracy	Type of the Location info.
NFC [4]	high	discontinuous
Visual Marker [5]	high	discontinuous
Light Beacon [6]	high	discontinuous
Ultrasonic Beacon [7]	high	discontinuous
Bluetooth Beacon [8]	medium	discontinuous
IMES [9], [10]	low	discontinuous
Wi-Fi Fingerprint [11], [12]	low	continuous
UWB TOA [13]	low	continuous
Wi-Fi Area Distinction [14]	low	continuous

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The Wi-Fi fingerprint technique is an RSSI-based positioning technique. This technique estimates the current position by using an RSSI vector map which is measured by a survey work. The user terminal can estimate its own position by comparing the current RSSI vector and the RSSI vector map using a maximum likelihood method. However, the Wi-Fi fingerprint technique has the following two major problems [16]:

- Complex installation: Incurs high-manpower costs, takes time for on-line site surveys
  Because much time is necessary to build a fingerprint database [16].
- Burdensome maintenance: Inflexibility to environmental dynamics

To avoid these major problems, the authors included a Wi-Fi location beacon and PDR module in their system. The Wi-Fi location beacon proposed in this paper is user-installable and is easy to maintain.

2. Related Work

An indoor positioning system consisting of Wi-Fi fingerprint and PDR module is proposed by Evennou et al. [15]. The architecture of Evennou's system is shown in **Fig. 1**. In Fig. 1, the left block drawn with a broken line is the Wi-Fi positioning module using the fingerprint technique and the right block drawn with a broken line is the PDR module. The output of these two modules is combined at the particle filter. The particle filter outputs a trajectory of the device and also feeds back corrective information to the PDR module.

Evennou's system has some problems since the system is based on the Wi-Fi fingerprint technique as shown in Fig. 1. In Evannou's system, the work of the top block, "RSS measurement" is very important for building the fingerprint database.

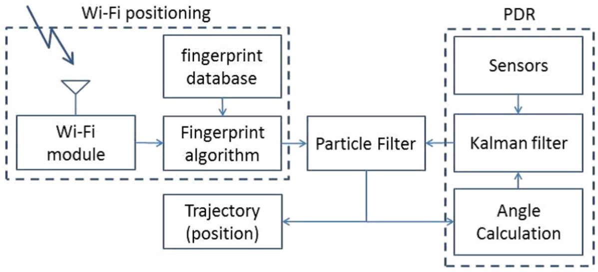

Fig. 1 Evennou's method (Wi-Fi fingerprint and PDR are combined).

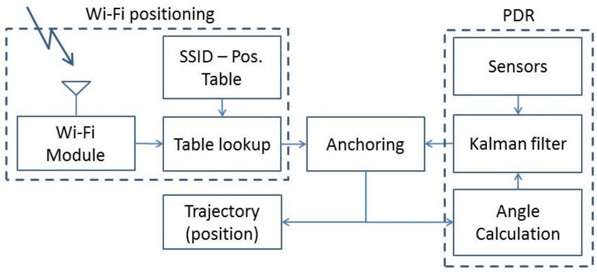

Fig. 2 Proposed system (based on a Wi-Fi location beacon and PDR module).

Here, RSS means "Received Signal Strength." Thus, in general, this work takes a long time because the fingerprint database needs to measure the RSS data uniformly over the entire service area. In addition, if the propagation characteristics are changed by rearranging the office furniture, the system installer has to rebuild the fingerprint database. These tasks require too much effort towards operating a Wi-Fi fingerprint system at the present day.

Therefore there is a requirement for a system that does not require so much extra work.

3. Proposed System

This section describes the proposed new indoor positioning system that combines a Wi-Fi location beacon and PDR module. Here, the Wi-Fi location beacon can be used instead of the Wi-Fi fingerprint of Evennou's system, because the Wi-Fi location beacon does not require any complex installation and maintenance work.

3.1 Wi-Fi Location Beacon

The Wi-Fi location beacon is a simple means of determining the position of users. All Wi-Fi radio access points that comply with the IEEE 802.11 standards can be a Wi-Fi beacon. These IEEE 802.11 standards stipulate that a Wi-Fi radio access point must transmit a broadcast beacon signal periodically (the transmission period is around 100 ms). Therefore, if a user device such as a smartphone, detects the beacon signal transmitted from the Wi-Fi access point, the positioning algorithm can determine the position of the device within the coverage area of the access point.

3.2 Architecture of the Proposed System

The basic architecture of the proposed system is shown in **Fig. 2**. As shown in Fig. 2, the Wi-Fi positioning module and the PDR module are combined in the proposed system. In Fig. 2, in the left block drawn with a broken line is the Wi-Fi positioning module based on the Wi-Fi location beacon, and the right block drawn with a broken line is the PDR module. In Fig. 2, the left block and the method of combining the systems are different from Fig. 1. An anchoring algorithm is used for combining the systems. The anchoring module is a simple means of linking the anchor position data from the Wi-Fi positioning module with the estimated trajectory data from the PDR module.

Here, the Wi-Fi positioning module which is surrounded with the left box of a broken line provides a current position data whenever the user terminal detects a signal of a Wi-Fi location beacon. Then, the "Anchoring" box records these current positions as anchor points to estimate a trajectory. The PDR module which is surrounded with the right box of a broken line provides a current position data calculated by a popular dead reckoning method [17]. Its "Angle calculation" calculates the direction of the user by using two or more coordination data of the anchor points. Finally, the trajectory of the user is calculated by the "Trajectory" box by those coordination data of the anchor points and direction of the estimated angle.

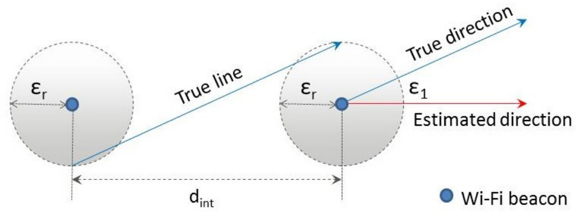

Fig. 3 Azimuth error ϵ_1 is caused by ϵ_r and d_{int}.

3.3 Detection Error Requirement for the Wi-Fi Location Beacon

To design a working version of the proposed system, it is necessary to clarify the margin of detection error of the Wi-Fi location beacon, because there is a trade-off between the detection error of the Wi-Fi location beacon and the d_{int}. In the proposed system, the Wi-Fi location beacon provides a fixed position for the user device, and the PDR module estimates the trajectory from the fixed position. The detection error ϵ_r depends on both the radiation pattern of the Wi-Fi location beacon and the condition or the environment of its installation area. Details about this thing are described in Sections 3.5 and 3.6. So the detection error ϵ_r and the installation interval d_{int} of the Wi-Fi location beacon decides the azimuth error ϵ_1 as shown in **Fig. 3**. Figure 3 shows that if ϵ_r gets bigger, ϵ_1 also gets bigger. However if d_{int} becomes longer, ϵ_1 becomes smaller because of the nature of the geometry. In addition, there are two more error factors in the azimuth. There are ϵ_2, caused by the offset of the gyroscope (see **Fig. 4**), and ϵ_3, caused by the sensitivity of the gyroscope (see **Fig. 5**). The sensitivity of the gyroscope is a basic characteristic which is measured in mV per degree per second (mV/deg/sec). This value is important to decide the positioning accuracy by the PDR. In Fig. 4, the blue line indicates the true locomotion of the user terminal, and the left, red plot indicates the estimated locomotion by the gyroscope. The right, red line and blue line make the error angle ϵ_2. In general, the estimated direction by a gyroscope

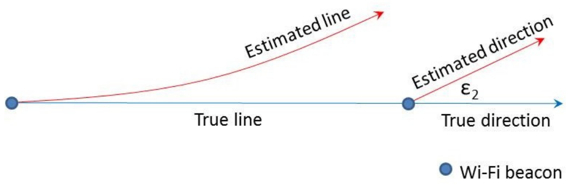

Fig. 4 Azimuth error ϵ_2 is caused by the offset of the gyroscope.

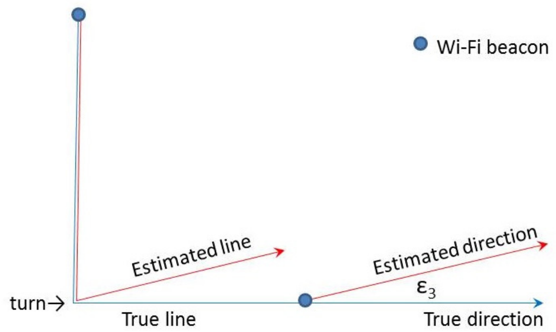

Fig. 5 Azimuth error ϵ_3 is caused by the sensitivity of the gyroscope.

has a detection error of angle due to its working condition. For example, the temperature characteristic of a gyroscope gives an offset error at its output of estimated angle. In Fig. 5, the blue line indicates the true locomotion with a turn of the user terminal, and the curved left, red line indicates the estimated locomotion by the gyroscope. The right red line and blue line make the error angle ϵ_3. In general, the estimated curve angle by a gyroscope has an error of angle due to its working condition. For example, the temperature characteristic of a gyroscope gives a sensing error at its output of estimated angle. The sensing error mainly depends on the temperature.

The total azimuth error of the PDR ϵ_{pdr} for the distance that a user walks is expressed in Eq. (1). As shown in Eq. (1), ϵ_{pdr} is expressed by a sum of all error factors by a gyroscope. Thus, the ϵ_{pdr} corresponds to the maximum error by the PDR module.

$$\begin{cases} \epsilon_{pdr} = \epsilon_1 + \epsilon_2 + \epsilon_3 \\ \epsilon_1 = \tan^{-1} \frac{\epsilon_r}{d_{int}} \end{cases} \tag{1}$$

To determine the margin of detection error of the Wi-Fi location beacon, the theoretical accumulation error is calculated as shown in **Fig. 6**. In Fig. 6, the horizontal axis is the installation interval of the Wi-Fi beacon (d_{int}), and the vertical axis is the accumulation error including ϵ_{pdr}. To derive Fig. 6, Eq. (1) was used with several kinds of ϵ_r, d_{int}, measured ϵ_2 and measured ϵ_3 by a preliminary experiment. Thus, the plots are the accumulation error for each d_{int} of distance traveled.

Next, the authors set the margin of positioning error of the proposed system as 5 m, since it is thought that 5 m of positioning margin reflects the typical case for indoor location services. Then, the authors had to decide the installation interval d_{int}. According to the results of Fig. 6, the installation interval d_{int} at 15 m can be set. Thus, 15 m of d_{int} can satisfy the required ϵ_r at less than 1 m based on Fig. 6.

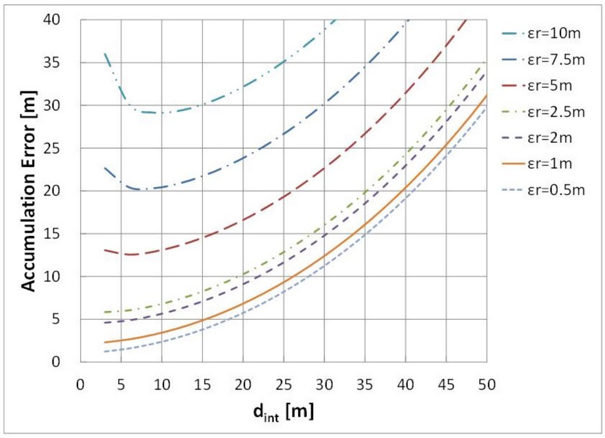

Fig. 6 Theoretical accumulation error of the proposed system.

Table 2 Implementation of the proposed Wi-Fi location beacon.

Term	Value
Wi-Fi specification	IEEE 802.11a (5 GHz band)
Antenna	gain: 14.5 dBi (4-patch array)
Direction of beam	downward
Antenna polarization	clockwise polarized wave
Transmission power	EIRP max
Beacon transmission interval	100 ms
Antenna height	2 to 3.6 m (ceiling)

3.4 Wi-Fi Location Beacon Transmission Power Requirement

The transmission power of the Wi-Fi location beacon must be as strong as possible to resist an interference from other wireless systems and noise. According to the measurement result shown in Fig. 12, the RSSI levels of most surrounding Wi-Fi stations are lower than −50 dBm. This means that the installer of the Wi-Fi location beacon does not have to consider the transmission power deeply. Because most transmission power of the Wi-Fi AP is enough to make a higher RSSI at the bottom point of the antenna (e.g., +10 dBm).

3.5 Implementation of a Wi-Fi Location Beacon

To realize a Wi-Fi location beacon that satisfies the requirements described in Sections 3.3 and 3.4, the authors designed the Wi-Fi location beacon as shown in **Table 2**.

In Table 2, Wi-Fi specification is IEEE 802.11a. This specification contributes to the smaller size of the antenna by using the 5 GHz band of the Wi-Fi. The specification of the antenna is decided its size and cost performance. This is because if the antenna is too large, the cost performance is poor. Also, if the antenna size is too small, it won't function well as a Wi-Fi location beacon. The direction of the beam is decided so that the ceiling is useful for installing a new device. The antenna polarization is decided as a clockwise polarized wave due to avoiding the polarization characteristics of the antenna. The transmission power is set to be as large as possible. The beacon transmission interval is decided to be a normal walking speed. The antenna height is decided as a height of the popular office environment. The user terminal can receive the Wi-Fi beacon signal every 100 ms time slot.

The implementation and working principle of the proposed Wi-

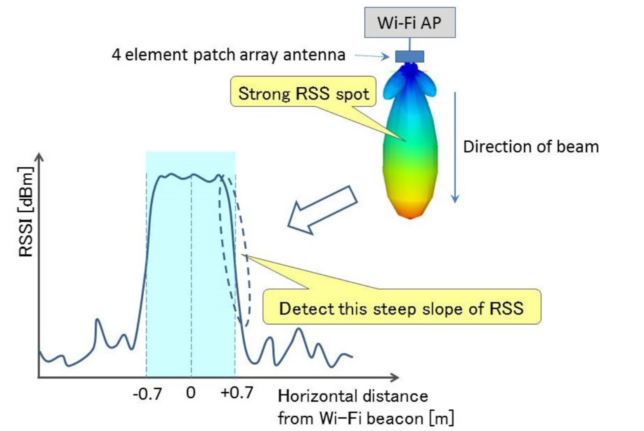

Fig. 7 Implementation and working principle of the proposed Wi-Fi location beacon.

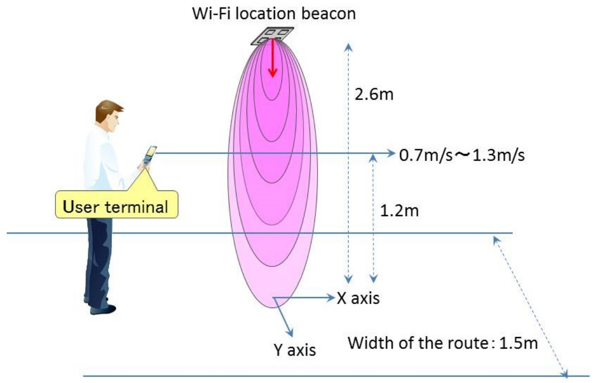

Fig. 8 Testbed for the Wi-Fi location beacon.

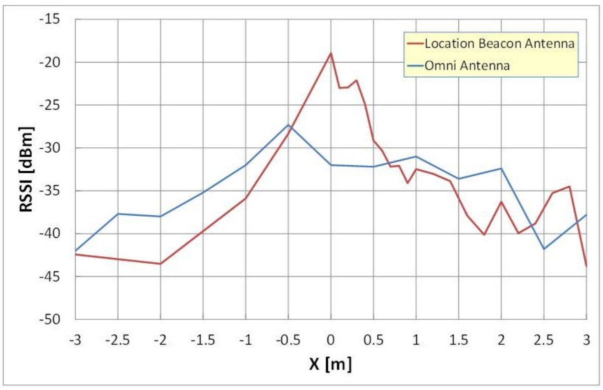

Fig. 9 RSSI measured on X axis.

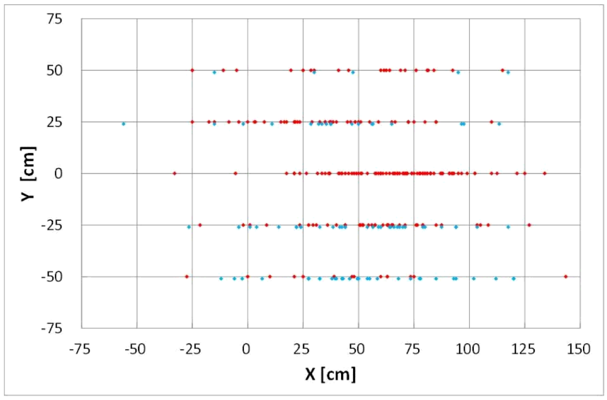

Fig. 10 Detected positions of the Wi-Fi spot.

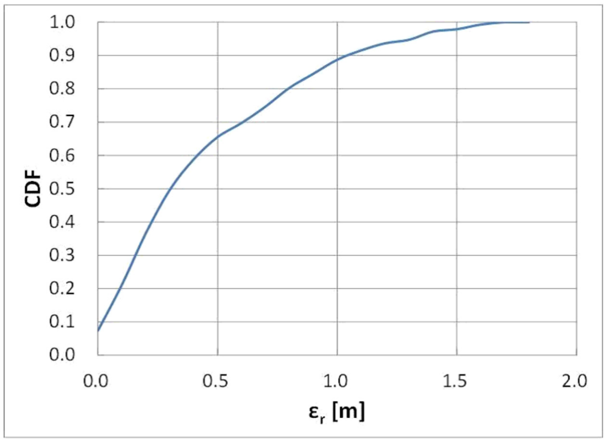

Fig. 11 CDF of the detection error of the Wi-Fi location beacon.

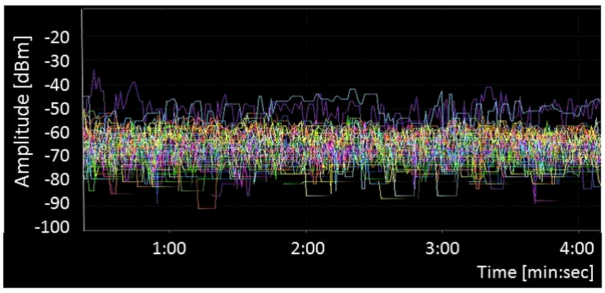

Fig. 12 Received signal of the surrounding Wi-Fi stations.

Fi location beacon is shown in **Fig. 7**. As shown in Fig. 7, the 4-element patch array antenna forms a hotspot with a strong RSS just below the antenna. The user device detects the hotspot by observing the steep slope of RSSI at around ±0.7 m from a point just below the antenna as shown in Fig. 7.

The basic positioning performance is checked by the testbed shown in **Fig. 8**. Figures 9 to 19 show the results of the test. **Figure 9** shows the measured RSSI along the X axis.

Figure 9 shows the steep slope of RSSI which is of a sufficient level for the user device to detect the Wi-Fi location beacon. In Fig. 9, the RSSI measured on the X axis by using an omni antenna is shown for comparison with the Wi-Fi location beacon antenna. Figure 9 shows that the location beacon antenna makes a higher RSSI spot than the omni antenna. This characteristic indicates that the proposed location beacon antenna is better than the omni antenna to work as a positioning beacon.

Detected positions by the Wi-Fi location beacon are plotted in **Fig. 10**. A user terminal detects when the RSSI level from the Wi-Fi location beacon is higher than the threshold level set for each beacon. The cumulative distribution function (CDF) of the detection error in Fig. 10 is shown in **Fig. 11**. Figure 11 indicates that 90% of the detection errors of this Wi-Fi location beacon are lower than 1 m.

Figure 12 shows the observed RSSI of the surrounding Wi-Fi stations. The RSSI levels of surrounding Wi-Fi stations are lower than the working range of the proposed Wi-Fi location beacon shown in Fig. 10. Therefore it is thought that the proposed Wi-Fi location beacon is strongly resistant to interference by other Wi-Fi systems and noise. In Figs. 11 to 13, these data are showed to introduce an actual example. So there are no references in these figures.

Finally, the authors evaluated the detection probability of the Wi-Fi location beacon. It was 100% for a stationary device, and 80% for a pedestrian, respectively.

3.6 Installation Requirements

Installation requirements of the proposed Wi-Fi location beacon are shown in this subsection. It is thought that several installation requirements from the point of view of radio propagation environments must be met to provide the positioning accuracy described above, because the proposed method uses the Wi-Fi radio wave of 5 GHz band. **Figure 13** shows measured RSSIs of the radio wave of the Wi-Fi location beacon installed on both a ceiling and a floor in an office environment. The horizontal axis is the horizontal distance between the Wi-Fi beacon and the user terminal. As shown in Fig. 13, the performance of the Wi-Fi beacon (or the characteristics of the measured RSSI) is dependent upon the installation surface of the Wi-Fi location beacon's antenna. Why? It is thought that the Wi-Fi location beacon installed on the floor made a multipath propagation around itself. Because there are some metal objects (for example, furniture like a cabinet) on the office floor. The source waves of the multipath are mainly sidelobes of the beacon wave transmitted by the antenna. On the other hand, it is thought that the Wi-Fi location beacon installed on the ceiling makes it difficult for generating a multipath propagation around itself because there are no metal object to reflect a radio wave around the antenna. The sidelobes which are source waves of the multipath can be traveled to far away. Since observing these phenomenons, the authors inferred that the installation requirements for the proposed Wi-Fi location beacon are necessary to avoid the effects from the objects around the antenna. The relationship between the *beacon spot* and the *object sensitive zone* are shown in **Fig. 14**. In Fig. 14, the "Object (influenceable)" means that the object on the floor has the capability to give bad effects to the detection accuracy of the Wi-Fi location beacon.

Therefore, the conditions about the installation of the antenna to obtain the proper accuracy of the location beacon were studied. The study was done by the Ray-Trace simulation. The five parameters for the simulation are below:

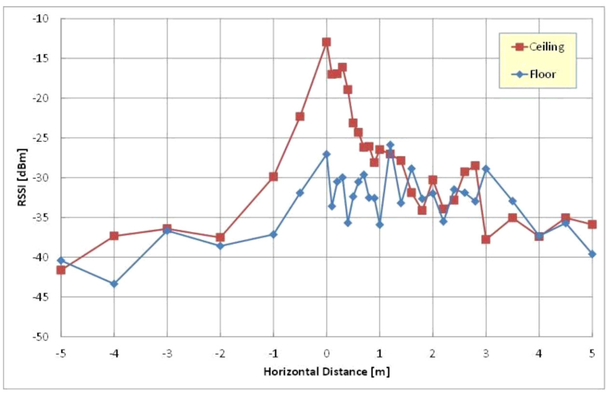

Fig. 13 RSSIs of the radio wave of the Wi-Fi location beacon installed on both a ceiling and a floor in an office.

- `Height` h: height of the antenna from the floor
- `Horizontal distance` d_w: horizontal distance between the wall and the antenna
- `Vertical space` d_v: vertical distance of the space between the object on the floor and the antenna
- `Horizontal space` d_h: horizontal distance of the space between the object and the wall
- `Tilt angle` θ: direction angle of the antenna's main lobe

The simulation result with parameter h is shown in **Fig. 15**. The horizontal axis and the vertical axis of this plot are height h and diameter of the beacon spot, respectively. In Fig. 15, the *diameter of the beacon spot* indicates the size of the RSSI's hot spot. The hot spot is observed on the surface of the 1.2 m high from the floor and is shaped by the precipitous slope of RSSI. The simulation was tried for 10 m high from the floor. However, it was impossible to shape the hot spot on the higher surface over 3.5 m. It is thought that this limitation appeared by spreading the radio wave's energy because of the distance from the antenna. From this result, the authors decided the requirement of the height h is lower than 3.5 m.

Next, the simulation result with parameter d_h is shown in **Fig. 16**. The horizontal axis and the vertical axis of this plot are distance of the horizontal space d_h and the diameter of the beacon spot, respectively. As shown in Fig. 16, the spot size becomes small steeply when d_h is shorter than 1 m. This simulation was

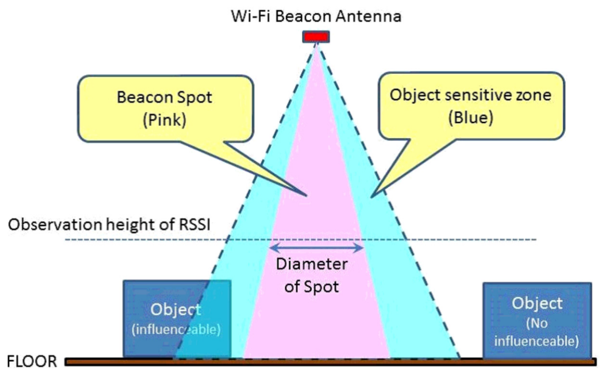

Fig. 14 Beacon spot and object sensitive zone.

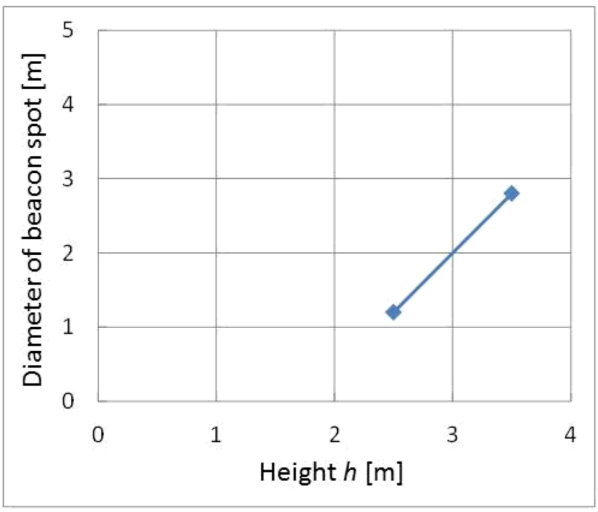

Fig. 15 Height h v.s. diameter of the beacon spot

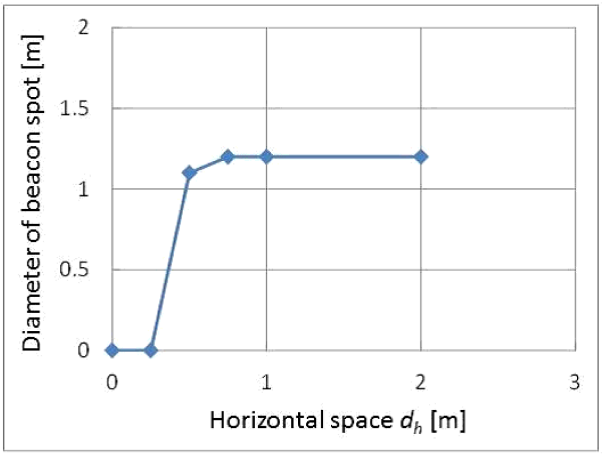

Fig. 16 Horizontal space d_h v.s. diameter of the beacon spot.

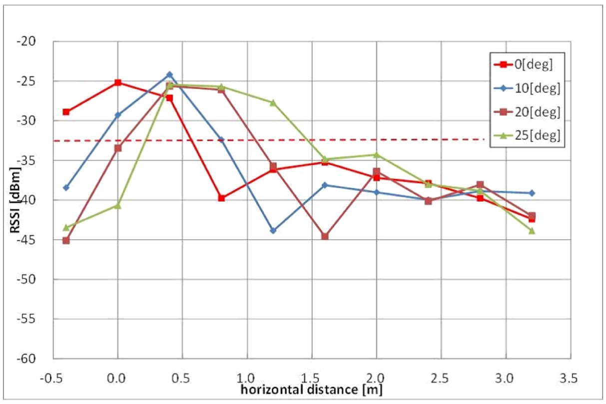

Fig. 17 Relationship between the tilt angle θ and the spot size.

done with 2.5 m of parameter h (typical).

Here, 1 divided by 2.5 is 0.4.

From these two results, it is thought that the spot size is affected by the wall whenever the d_w is shorter than $0.4h$.

The relationships between the tilt angle of the Wi-Fi antenna θ and the spot size are shown in **Fig. 17**. In Fig. 17, the experimental results by four kinds of θ are plotted. The horizontal axis and the vertical axis of this plot are the horizontal distance from the antenna and the RSSI, respectively. Here, positions of these steep slopes of the RSSI indicate the spot size. As shown in Fig. 17, the center position of the spot and the spot size correspond to the tilt angle. The distance between the center position of the spot and the antenna becomes longer when the tilt angle is bigger. Also, the spot size becomes bigger when the tilt angle is bigger. From these results, it is thought that the requirement for the tilt angle θ is less than 10 deg.

According the results of the studies, the installation requirements of the proposed Wi-Fi location beacon are summarized as shown in **Fig. 18**. In Fig. 18, the "Object (influenceable)" is same object described at Fig. 14.

Therefore, the decision algorithm for the installation position/place of the Wi-Fi location beacon antenna can be shown as following:

(1) Prepare the layout map of the installation area
(2) Draw lines along all the walkable way at the layout
(3) Mark dots on the lines with 15 m of interval

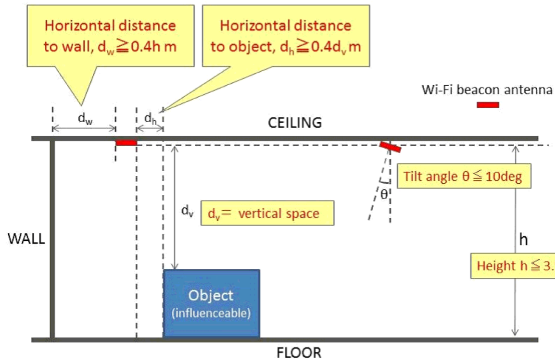

Fig. 18 Requirements of the Wi-Fi beacon installation.

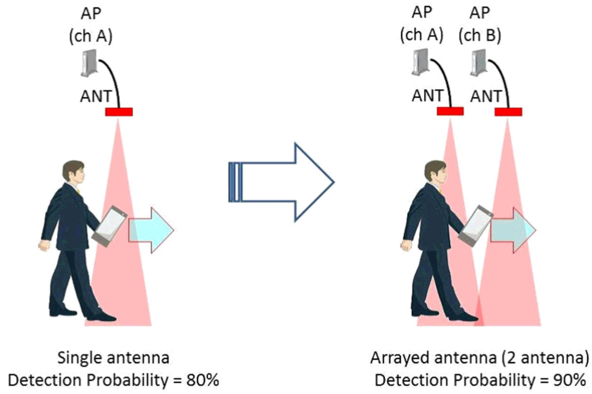

Fig. 19 Arrayed antenna for a Wi-Fi location beacon.

(4) Check the marked position satisfy the condition shown in Fig. 18
(5) If all of the marked positions satisfy the condition → Finish
(6) If not, move the marked position which doesn't satisfy the condition to another position
(7) Continue 4 to 6 until all the marked positions satisfy the condition shown in Fig. 18

In Fig. 18, there is no recommended value in parameter d_v.

3.7 Arrayed Wi-Fi Location Beacon

As described above, the detection probability of the Wi-Fi location beacon is 80% for a pedestrian's device. This detection probability depends on the beacon transmission period and walking speed of the pedestrian. The current beacon transmission period is 100 ms. It is best to have a shorter beacon transmission period than 100 ms to improve the detection probability. However, this is not recommended because the transmission duty-cycle of the Wi-Fi common control signal will become congested (the Wi-Fi beacon signal is one of the Wi-Fi common control signals) because IEEE802.11's Wi-Fi adopt the CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance). CSMA/CA stops the transmit when other signals in same channel were sensed with a strong RSSI. Therefore, the authors considered using an arrayed antenna for the Wi-Fi location beacon. As shown in **Fig. 19**, it is thought that the detection probability can be improved if the beacon antenna is set in a series of two or more along the walking route.

After consideration, the three layouts of arrayed antenna were tested as shown in **Fig. 20**.

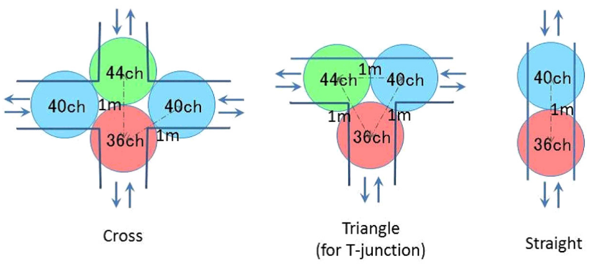

Fig. 20 Test layout of arrayed antenna.

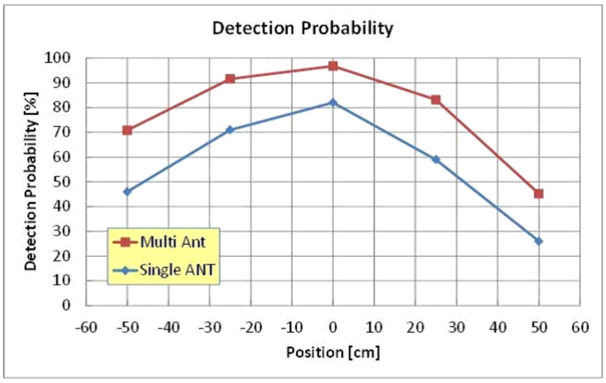

Fig. 21 Detection probability of the single/multi antenna Wi-Fi location beacon.

Thus, to evaluate the total detection probability of a Wi-Fi location beacon with arrayed antennas, the authors evaluated the three antenna layouts as shown in Fig. 20. The transmission channels were set differently for each antenna. In Fig. 20, each layout is suitable for the three types of intersection or the straight way. If the shape of the intersection is a cross, the left layout in Fig. 20 is the most suitable, or if the shape of the intersection is T, the center layout in Fig. 20 is the most suitable. Also, of course, in case of the straight way, the right layout in Fig. 20 is the most suitable. The total detection probability of the Wi-Fi location beacon with the "Straight layout" in Fig. 20 of arrayed antenna is shown in **Fig. 21**. In Fig. 21, the horizontal axis indicates the X axis in Fig. 8. This shows the result of the straight layout of Fig. 20 for the example result. As shown in Fig. 21, the total detection probability of the Wi-Fi location beacon with an arrayed antenna gains about 15 to 20%.

Thus, it is thought that the layout shown in Fig. 21 satisfies the required error margin described in Section 3.3.

3.8 Effect of the Proposed Wi-Fi Location Beacon

As description in Sections 3.1 to 3.7, it is expected that the proposed method achieves spot locating means by using Wi-Fi with a greater accuracy and a better anti-interference. Also, it is expected to achieve the indoor positioning system for a pedestrian who has a good performance as shown above by combining the proposed method and PDR. By the way, the BLE beacon [8] has become popularized these days. Thus, the authors describe the advantages of the Wi-Fi location beacon. Almost no BLE beacons use a beam antenna like the Wi-Fi location beacon antenna. Furthermore, the transmission power is lower than that of the Wi-Fi location beacon. Therefore, the BLE beacon is weaker than the Wi-Fi location beacon at the point of view of the interference or the environment robustness. However, the power consumption of the BLE beacon is lower than that of the Wi-Fi location beacon. Which beacon is better? It depends on the user requirement for the system.

3.9 Comparison with Wi-Fi Fingerprint

In a typical Wi-Fi fingerprint system, Wi-Fi access points are installed for the network infrastructure So these access points are installed at about 15 m of distance apart. This distance indicates that the density of these access points is shown by Eq. (2) [20].

$$D = 1/2.6R^2 \tag{2}$$

In Eq. (2), D is a density of the Wi-Fi access point, and R is an interval of each access points. From Eq. (2), the typical D is 0.0017 access points per 1 m^2. On the other hand, the Wi-Fi location beacon is also installed at about 15 m of distance (The reason of this value is described in Section 4). So, the densities of the Wi-Fi location beacon and the Wi-Fi fingerprint are almost the same. Therefore, the installation cost and the operation cost of these two systems are very close.

3.10 Comparison with BLE Beacon

Next, the authors consider the comparison with the BLE beacon. Because the BLE beacon is very popular these days. The valid wireless range by a BLE beacon is very short. It's about 1 m to 10 m. Therefore, the disadvantage of the BLE beacon is the number of devices. In addition, the battery maintenance is also a disadvantage of the BLE beacon because it is necessary to exchange the battery of the BLE beacon. The authors think that the Wi-Fi location beacon has an advantage at these points. However the total cost of the Wi-Fi location beacon is higher than that of the BLE beacon because BLE devices are cheaper than Wi-Fi devices.

4. Preliminary Evaluation

In this section, preliminary evaluation results of an indoor positioning system based on the Wi-Fi location beacon and PDR module were shown with experiments to confirm the availability of the Wi-Fi location beacon. The results shown in this section can serve as a useful reference for future study and are a good evidence of this work. The architecture of the preliminary evaluation system is shown in Section 3.2.

4.1 Experimental System

The experimental system consists of a set of four arrayed Wi-Fi location beacons installed in the ceiling, and a user device installed with a test-tool software. The test-tool software is composed of a Wi-Fi location beacon detector and a trajectory estimator using the PDR technique. When a signal transmitted from any Wi-Fi location beacon reaches the user device, the software compares the RSSI with the threshold value to determine that the current position is immediately below the Wi-Fi location beacon. The position of the user device is decided by the table lookup algorithm. The lookup table contains the coordination data of all the Wi-Fi location beacons in the test field, so the test-tool soft-

Table 3 Implementation of the PDR module.

Term	Value
Posture detection	3-axis accelerometer
Orientation detection	3-axis gyroscope
Sampling period of sensors	20 ms
Posture estimation	Kourogi's method [17]
Speed estimation	Yamazaki's method [18]

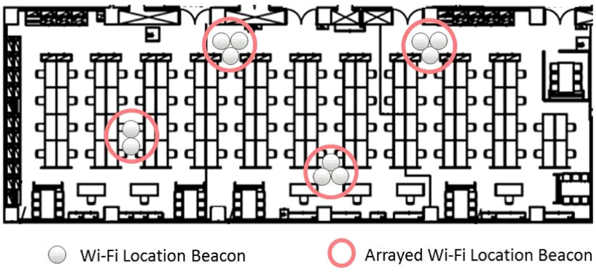

Fig. 22 Test environment for the proposed method.

Table 4 Test conditions.

Term	Value
Wi-Fi AP	JRL-710AL3 (Japan Radio Co.)
User device	Nexus 7 (Google Co.)
Band	W52 (5 GHz)
Beacon Install Interval	12 to 15 m (in the passageway)
Type of Room	Office (11 × 35 m)
Passageway width	1.5 m
Ceiling height	2.6 m
Tester	Man in 20's
Use case	Navigation (Hand held)
Number of test routes	9

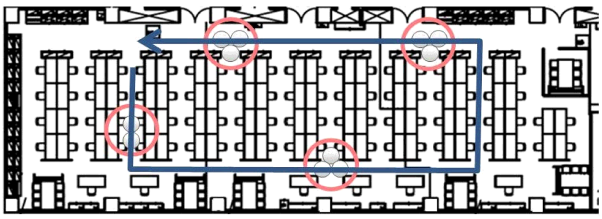

Fig. 23 Test route A.

ware can recognize the current true position of the user device whenever a Wi-Fi location beacon is detected. In addition, the PDR module calculates the trajectory of the user device using sensed data and the last two fixed position data of detected Wi-Fi location beacons. The sensed data is used for estimating the trajectory, and the two fixed position data are used for the anchor point data of the PDR module. The implementation of the PDR is shown in **Table 3**.

The evaluation experiment was carried out in the author's office. The experimental system consists of four beacon arrays set in the ceiling (see **Fig. 22**) and a user device carried by a tester. The test conditions are shown in **Table 4**.

4.2 Routes

In this evaluation, there were nine test routes. Three typical routes are shown in **Figs. 23** to **25**. The tester walked along these routes.

4.3 Results

The results for the estimated trajectories using the proposed

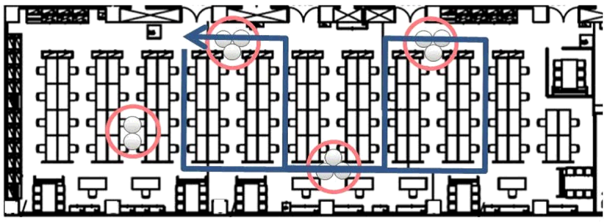

Fig. 24 Test route B.

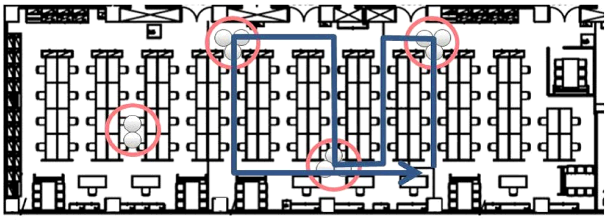

Fig. 25 Test route C.

Fig. 26 Estimated trajectory (route A).

Fig. 27 Estimated trajectory (route B).

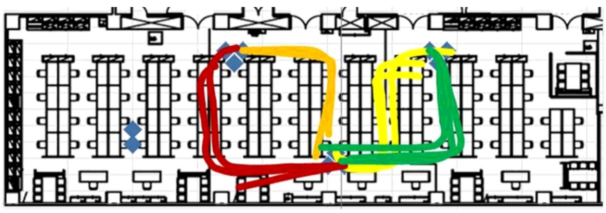

Fig. 28 Estimated trajectory (route C).

method are shown in **Figs. 26** to **28**. From these results, azimuth estimation errors at a Wi-Fi location beacon causing orientation errors can be observed. It is thought that this kind of error mainly occurs due to ϵ_r, a detection error of the Wi-Fi location beacon. However the proposed system does not have a complicated algorithm such as a particle filter for smoothing the trajectory, and according to these results, all of the estimated trajectories can be considered to be an almost true route. Therefore it is thought that the proposed system can work in an indoor positioning system with sufficient accuracy even with a light algorithm.

For numerical evaluation, the cumulative distribution function (CDF) of the positioning error for all nine routes are shown in **Fig. 29**. The continuous line indicates the CDF of the proposed system, and the dashed line indicates Evonnou's system described

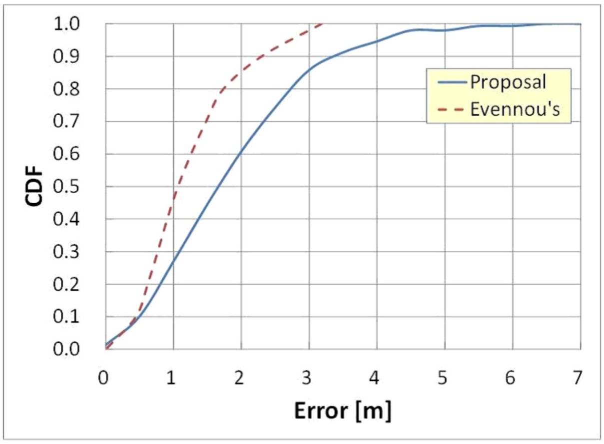

Fig. 29 CDF of the positioning error on the estimated trajectory.

in Section 2.

According to Fig. 29, Evonnou's system performed with about 1 m better accuracy at 90% of CDF. Here, the authors believe that the difference between these two accuracies came from the insufficiency of the optimization on the PDR module in the proposed system. In other word, the accuracy by the proposed method on Fig. 29 should be close or fit to the Evannon's result if the parameter of the PDR module will be optimized. Because the authors did not optimize the parameters of the PDR module during the evaluation. The parameters are bias voltage, angular acceleration sensitivity and acceleration-insensitive drift rate. However, the proposed system is better from the point of view of the installation and maintenance work involved, since the burdensome installation work such as building a Wi-Fi fingerprint database and maintaining it afterwards are not necessary. The problems at a Wi-Fi fingerprint method was mentioned by Taniuchi [19].

5. Conclusion

This paper proposed a new type of wireless beaconing method called a Wi-Fi location beacon, and showed its basic positioning performance based on experimental results. In addition, the experimental result show the trajectory tracking performance of the indoor positioning system using the proposed Wi-Fi location beacon and PDR module. The Wi-Fi location beacon achieves positioning accuracy to within 1 m by using a high gain beam antenna. The proposed method can be used for indoor positioning systems with sufficient accuracy, despite using a lighter algorithm than previous systems. It also has advantages for installation and maintenance. Therefore it is thought that the proposed system can be installed by users.

In future work, the authors would like to study ways of using Wi-Fi location beacon antennas as part of the wider communication infrastructure.

References

[1] Sassi, A. and Zambonelli, F.: Coordination Infrastructures for Future Smart Social Mobility Services, *IEEE Intelligent Systems*, Vol.29, No.5 (2014).

[2] Sassi, A., Mamei, M. and Zambonelli, F.: Towards a general infrastructure for location-based smart mobility services, *Proc. HPCS2014*, pp.849–856 (2014).

[3] Hofmann-Wellenhof, B., Lichtenegger, H. and Wasle, E.; GNSS – Global Navigation Satellite Systems, Springer Vienna, ISBN:978-3-211-73012-6 (2008).

[4] ISO/IEC: International Standard ISO/IEC 18092:2013, Information technology – Telecommunications and information exchange between systems – Near Field Communication – Interface and Protocol (NFCIP-1) (2013).

[5] Nakazato, Y., Kanbara, M. and Yokoya, N.: Discreet markers for user localization, *Proc. ISWC2004*, pp.172–173 (2004).

[6] Arafa, A., Jin, X. and Klukas, R.: Wireless Indoor Optical Positioning With a Differential Photosensor, *IEEE Photonics Technology Letters*, Vol.24, No.12 (2012).

[7] Kim, S.J. and Kim, B.K.: Dynamic Ultrasonic Hybrid Localization System for Indoor Mobile Robots, *IEEE Trans. Industrial Electronics*, Vol.60, No.10 (2013).

[8] Fernandez, T.M., Rodas, J., Escudero, C.J. and Iglesia, D.I.: Bluetooth Sensor Network Positioning System with Dynamic Calibration, *Proc. ISWCS2007*, pp.45–49 (2007).

[9] Kohtake, N., Morimoto, S., Kogure, S. and Manandhar, D.: Indoor and Outdoor Seamless Positioning using Indoor Messaging System and GPS, *Proc. IPIN2011* (2011).

[10] Troyk, P.R., DeMichele, G.A., Kerns, D.A. and Weir, R.F.: IMES: An Implantable Myoelectric Sensor, *Proc. EMBS2007*, pp.1730–1733 (2007).

[11] Bahl, P. and Padmanabhan, V.: RADAR: An in-building RF-based user location and tracking system, *Proc. INFOCOM2000*, pp.775–784 (2000).

[12] Prasithsangaree, P., Krishnamurthy, P. and Chrysanthis, P.K.: On Indoor Position Location With Wireless Lans, *Proc. PIMRC2002*, pp.720–724 (2001).

[13] Fujiwara, R., Mizugaki, K., et al.: TOA/TDOA Hybrid Relative Positioning System Based on UWB-IR Technology, *IEICE Trans. Comm.*, Vol.94B, No.4, pp.1016–1024 (2011).

[14] Hotta, S., Hada, Y. and Yaginuma, Y.: A Robust Room-level Localization Method Based on Transition Probability for Indoor Environments, *Proc. IPIN2012* (2012).

[15] Evennou, F. and Marx, F.: Advanced Integration of WiFi and Inertial Navigation Systems for Indoor Mobile Positioning, *EURASIP Journal on Applied Signal Processing*, Vol.2006, No.1, 164 (2006).

[16] Zou, H., Jiang, H., Lu, X. and Xie, L.: An online sequential extreme learning machine approach to WiFi based indoor positioning, *Proc. IEEE World Forum on IoT2014* (2014).

[17] Kourogi, M. and Kurata, T.: Personal Positioning based on Walking Locomotion Analysis with Self-Contained Sensors and a Wearable Camera, *Proc. ISMAR2003*, pp.103–112 (2003).

[18] Yamazaki, M. and Sato, H.: Human Walking With Reference to Step Length, Cadence, Speed and Energy Expenditure, *Journal of the Anthropological Society of Nippon*, Vol.98, No.4, pp.385–401 (1990).

[19] Taniuchi, D. and Maekawa, T.: Robust Indoor Positioning Method Based on Automatic Update of Wi-Fi Fingerprints, *IPSJ Journal*, Vol.55, No.1, pp.280–288 (2014).

[20] Adachi, F.: Cellular theory, available from ⟨http://www.mobile.ecei.tohoku.ac.jp/lecture/application/application_07.pdf⟩.

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