

Research and Applications

Smart hospital infrastructure: geomagnetic in-hospital medical worker tracking

Keiko Yamashita,¹ Shintaro Oyama,^{1,2} Tomohiro Otani,³ Satoshi Yamashita,^{1,2}
Taiki Furukawa,^{1,2} Daisuke Kobayashi,^{1,2,4} Kikue Sato,^{1,2} Aki Sugano,^{1,2} Chiaki
Funada,^{1,2} Kensaku Mori,⁵ Naoki Ishiguro,⁶ and Yoshimune Shiratori^{1,2}

¹Medical IT Center, Nagoya University Hospital, Nagoya, Japan, ²Center for Healthcare Information Technology (C-HiT), Nagoya University, Nagoya, Japan, ³NTT DATA Corporation Technology Innovation Headquarters, Tokyo, Japan, ⁴Division of Medical and Healthcare Systems, Kobe University Graduate School of Medicine, Kobe, Japan, ⁵Department of Intelligent Systems, Graduate School of Informatics, Nagoya University, Nagoya, Japan, and ⁶Graduate School of Medicine, Nagoya University, Nagoya, Japan

Corresponding Author: Keiko Yamashita, Medical IT Center, Nagoya University Hospital, Nagoya, Aichi, Japan (kei-yamashita@med.nagoya-u.ac.jp)

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ABSTRACT

Purpose: Location visualization is essential for locating people/objects, improving efficiency, and preventing accidents. In hospitals, Wi-Fi, Bluetooth low energy (BLE) Beacon, indoor messaging system, and similar methods have generally been used for tracking, with Wi-Fi and BLE being the most common. Recently, nurses are increasingly using mobile devices, such as smartphones and tablets, while shifting. The accuracy when using Wi-Fi or BLE may be affected by interference or multipath propagation. In this research, we evaluated the positioning accuracy of geomagnetic indoor positioning in hospitals.

Materials and Methods: We compared the position measurement accuracy of a geomagnetic method alone, Wi-Fi alone, BLE beacons alone, geomagnetic plus Wi-Fi, and geomagnetic plus BLE in a general inpatient ward, using a geomagnetic positioning algorithm by GiPStech. The existing Wi-Fi infrastructure was used, and 20 additional BLE beacons were installed. Our first experiment compared these methods' accuracy for 8 test routes, while the second experiment verified a combined geomagnetic/BLE beacon method using 3 routes based on actual daily activities.

Results: The experimental results demonstrated that the most accurate method was geomagnetic/BLE, followed by geomagnetic/Wi-Fi, and then geomagnetic alone.

Discussion: The geomagnetic method's positioning accuracy varied widely, but combining it with BLE beacons reduced the average position error to approximately 1.2 m, and the positioning accuracy could be improved further. We believe this could effectively target humans (patients) where errors of up to 3 m can generally be tolerated.

Conclusion: In conjunction with BLE beacons, geomagnetic positioning could be sufficiently effective for many in-hospital localization tasks.

INTRODUCTION

Recently, as position-tracking technologies have developed, many services have taken advantage of technologies for tasks such as

navigation and route finding.¹ Both indoor and outdoor positioning technologies are available. A prominent example of outdoor positioning technology is Global Positioning System (GPS),² which

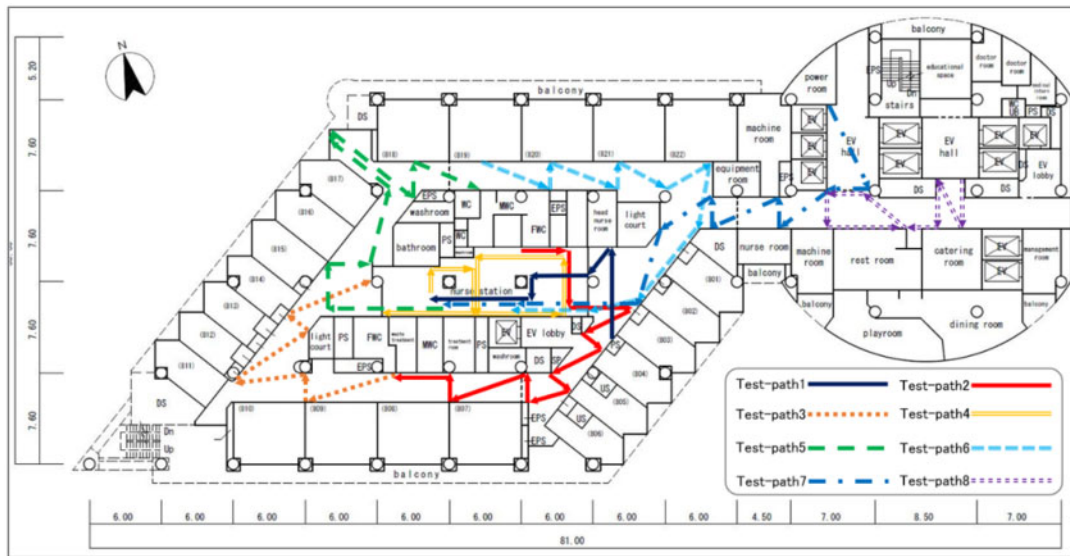


Figure 1. The 8 test routes.

uses radio waves received from satellites. However, such outdoor technologies cannot be applied to indoor environments, as they shield the receiver from the incoming satellite radio waves,³ (ie, until recently, it has been difficult to develop information and communication technologies that can provide practical indoor positioning).

This changed with the advent of technologies such as Wi-Fi,³ Bluetooth low energy (BLE) beacon,⁴ radio-frequency identification,⁵ and the indoor messaging system (IMES).⁶ Many facilities have already adopted Wi-Fi, which has the advantage of already being part of the existing infrastructure, although this can cause interference from environmental factors, such as the presence and movement of people.⁷ Additionally, transmitters must be installed, which can be expensive when many are required. Contrastingly, BLE beacons offer higher accuracy than Wi-Fi,⁸ with cheaper units whose low power consumption means they can be battery-powered, making them easier to introduce. Although individual radio-frequency identification tags are very inexpensive, many gates are needed, they can only cover a limited range around a given gate, and frequent maintenance is required.⁹ Since IMES uses the same radio format as GPS, it can seamlessly acquire the current position both indoors and outdoors, but IMES transmitters must be installed so that devices, such as GPS-enabled smartphones, can receive the signals.

Another, geomagnetism-based, position-estimation technique matches measured magnetic field information with a magnetic field map derived from the current building's indoor magnetic field characteristics. This method has the advantage that, since there is a natural magnetic field everywhere, it can be used in places where Wi-Fi positioning is impossible, due to radio wave interference, lack of a power supply, or where installing BLE beacons is difficult; and it does not require any significant capital investment.

Recently, hospitals and other medical facilities have increasingly come to rely on location information. Being able to accurately locate patients, doctors, nurses, and medical devices enables them to respond promptly when nurses call from the hospital's public areas, observe the patient occupancy situation at a glance, and keep track of medical equipment and toilet occupancy, thereby improving oper-

ational efficiency and preventing medical accidents.¹⁰ Analyzing the accumulated data can also lead to improved working practices by identifying nurses' peak activity times and quantifying their overall workloads.

Our hospital (Nagoya University Hospital) is attempting to visualize both human beings and objects in an effort to improve operational efficiency and prevent medical accidents, examining the current locations of patients and medical staff in the hospital in an attempt to identify inefficiency in a way that was hitherto thought impossible. Utilizing advanced technology and information and communication technologies, we are developing a new medical "smart hospital concept," connecting locations and families by improving hospital efficiency and providing safe and secure medical care.

To achieve these operational efficiency improvements, we needed to gather position information and visualize the movements of people and goods. We also distributed smartphones to nurses to create an environment where we could continuously acquire such location information. This led us to focus on a geomagnetism-based method. Although other studies have attempted to measure position using smartphones with BLE⁴ beacons, we believe geomagnetism-based methods should not be neglected, motivating us to evaluate their potential.

We have adopted GiPStech technology¹¹ that can be used in all kinds of applications and can be positioned without the need for expensive equipment. It can also combine geomagnetism, BLE beacons, and Wi-Fi data to generate position measurements.

MATERIALS AND METHODS

Experiment 1: Geomagnetic, Wi-Fi, BLE, and their combined positioning accuracy measurement

Nagoya University Hospital's wards cover 14 stories, and we chose to conduct positioning experiments on the 8th floor (8W) ward, as this is in the center of the building where the impact of the building's structure on measurements is likely to be highest. For the set of test routes, we selected a route that included all the conditions for entering and exiting the hospital room from an elevator or a nurse station with many objects (Figure 1, test-path1). For these routes, the differ-

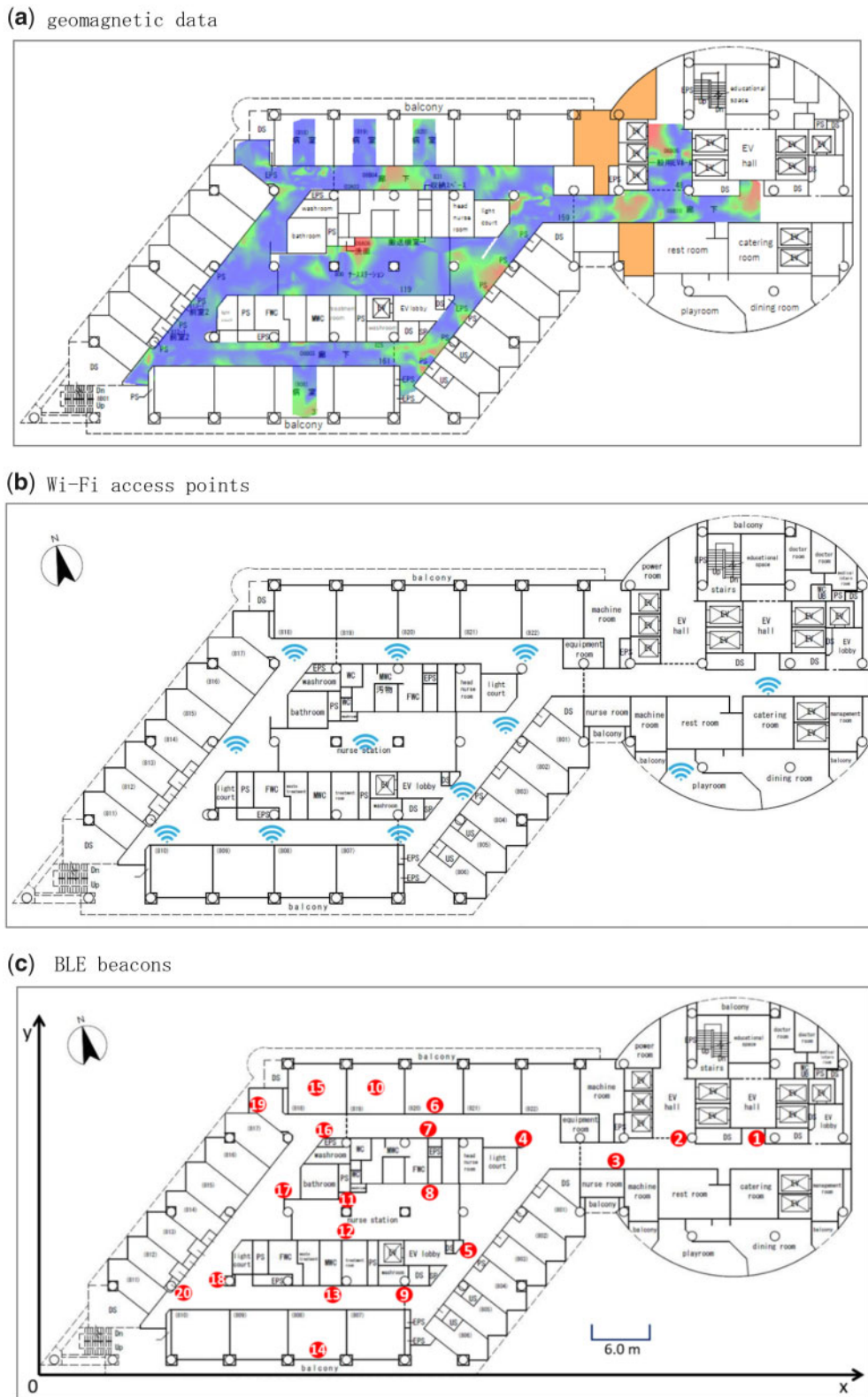


Figure 2-1. Building maps, showing (a) geomagnetic data, (b) Wi-Fi access points, and (c) BLE beacons.

ence between the measured position and the actual position was measured using geomagnetism only, Wi-Fi only, BLE only, geomagnetism in combination with Wi-Fi, and geomagnetism in combination with BLE.

Comparing the accuracy of geomagnetic, Wi-Fi, and BLE positioning

To select a suitable set of test routes, we interviewed healthcare workers about their actual work patterns and chose 7 test paths cov-

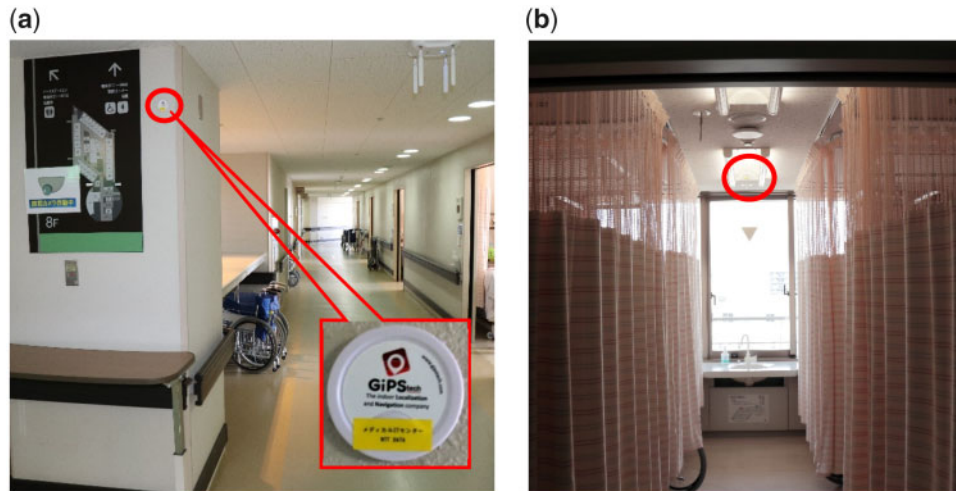


Figure 2-2. BLE beacons in (a) a corridor and (b) a hospital room.

ering all the wards (Figure 1). For these routes, we measured the differences between the measured and actual positions. We compared the positioning accuracy of 3 approaches: geomagnetism only, geomagnetism with Wi-Fi, and geomagnetism with BLE.

Geomagnetic positioning method

The local magnetic field is affected by magnetic materials such as the building's steel frame, and the geomagnetic field is different at each location. Magnetometers, sensors for measuring magnetic fields, have become ubiquitous in smartphones. These magnetometers are what enables the phone's compass to function. The simplest way of measuring the field strength of the earth's magnetic field would be to simply take the vector sum of the field strength contributions in each spatial direction.¹² We therefore measured these materials' magnetic field characteristics using a smartphone-based magnetic sensor (ARROWS M357/Fujitsu/Japan). To estimate the current position, we first registered this magnetic field information (map) in the GiPStech database prior to the experiments (Figure 2-1a). During the experiments, the current position was calculated by comparing the geomagnetic map with continuous magnetic vector measurements made by the user's device, and using pedestrian dead reckoning (PDR)¹³ based on applying a particle filter algorithm to user behavior data.

Wi-Fi positioning method

For positioning, we identified the locations of 12 existing wireless access points (Cisco Aironet 3700i/Cisco/America) from the building schematic (Figure 2-1b), then mapped their signal strengths using a smartphone. This enabled us to calculate the current position by comparing the measured Wi-Fi signal strength with the Wi-Fi signal strength map.

BLE beacon positioning method

For BLE positioning, we installed 20 BLE beacons (IBKS 105/Accent Systems/America) in the ward and noted their locations (Figure 2-1c). The beacons were installed on the corridor and nurses' station walls at a height of 2 m (Figure 2-2a). Since it was difficult to install them on the hospital room walls, we installed them in ceiling light fixtures at a height of 3 m (Figure 2-2b). The exact beacon locations are listed in Table 1. We then triangulated the user's position by esti-

imating each beacon's distance based on its signal strength (as for Wi-Fi) and combining the distances with the beacon location data.

Experiment 2: Verifying the accuracy of combined geomagnetic and BLE positioning

In Experiment 2, after consulting with the medical staff (doctors and nurses) working in the ward, we identified the following routes, based on their actual work patterns (Figure 3).

1. Route 1: Professor's route when visiting all patients
2. Route 2: Doctor's route when visiting all patients
3. Route 3: Nurses' typical route

We then measured for each route, each staff member's location as they followed these routes to evaluate the positioning accuracy of the most accurate method, as determined by Experiment 1.

Ground truth data

To prepare a dataset of correct (ground truth) position information, we affixed barcodes to the walls in the doorways of patient rooms at a height of 1.5 m (Figure 4). These were 1-dimensional barcodes, 4 cm × 2.8 cm in size, created according to the JAN-8 standard with a total of 8 digits, the first 4 identifying the location and the other 4 being the serial number. We acquired barcode images using a smartphone (via its built-in camera) and matched the barcode information to the actual position using a Java application of our own design. This

Table 1. Beacon locations according to the coordinate system shown in Figure 2c

Beacon no.	x (cm)	y (cm)	Beacon no.	x (cm)	y (cm)
1	8743	5474	11	4485	4736
2	8014	5483	12	4401	4460
3	7200	5181	13	4283	3982
4	6287	5449	14	4132	3320
5	5583	4342	15	4116	6086
6	5323	5759	16	4267	5524
7	5272	5516	17	3789	4963
8	5197	5030	18	3169	4032
9	5072	3974	19	3437	5885
10	4728	6086	20	2640	3907

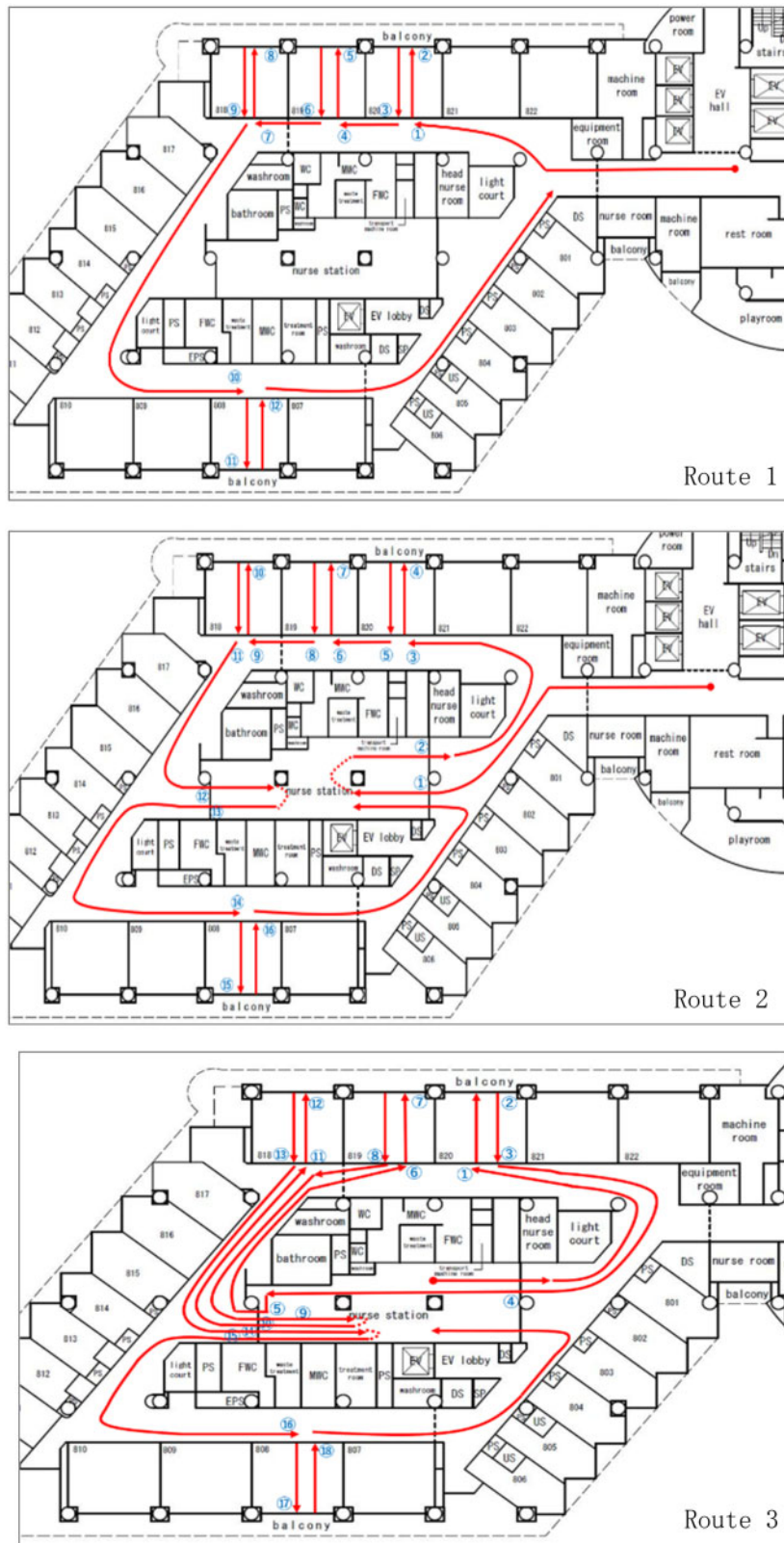


Figure 3. Routes 1–3 used for Experiment 2.

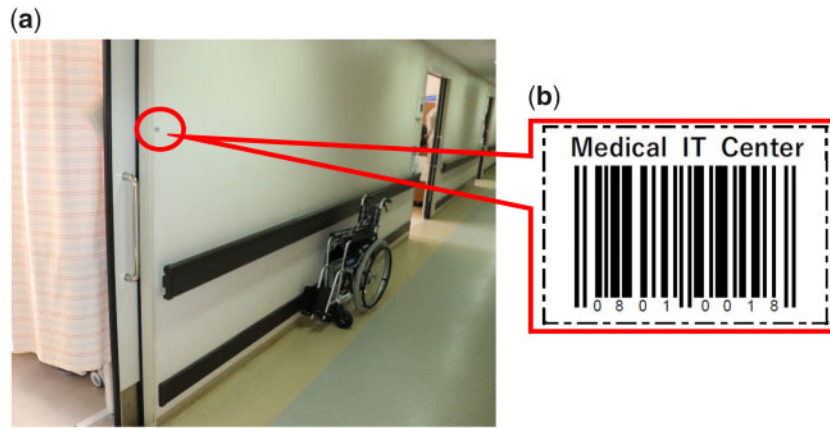


Figure 4. Hospital room entrance barcode (a) as seen from the corridor and (b) in detail.

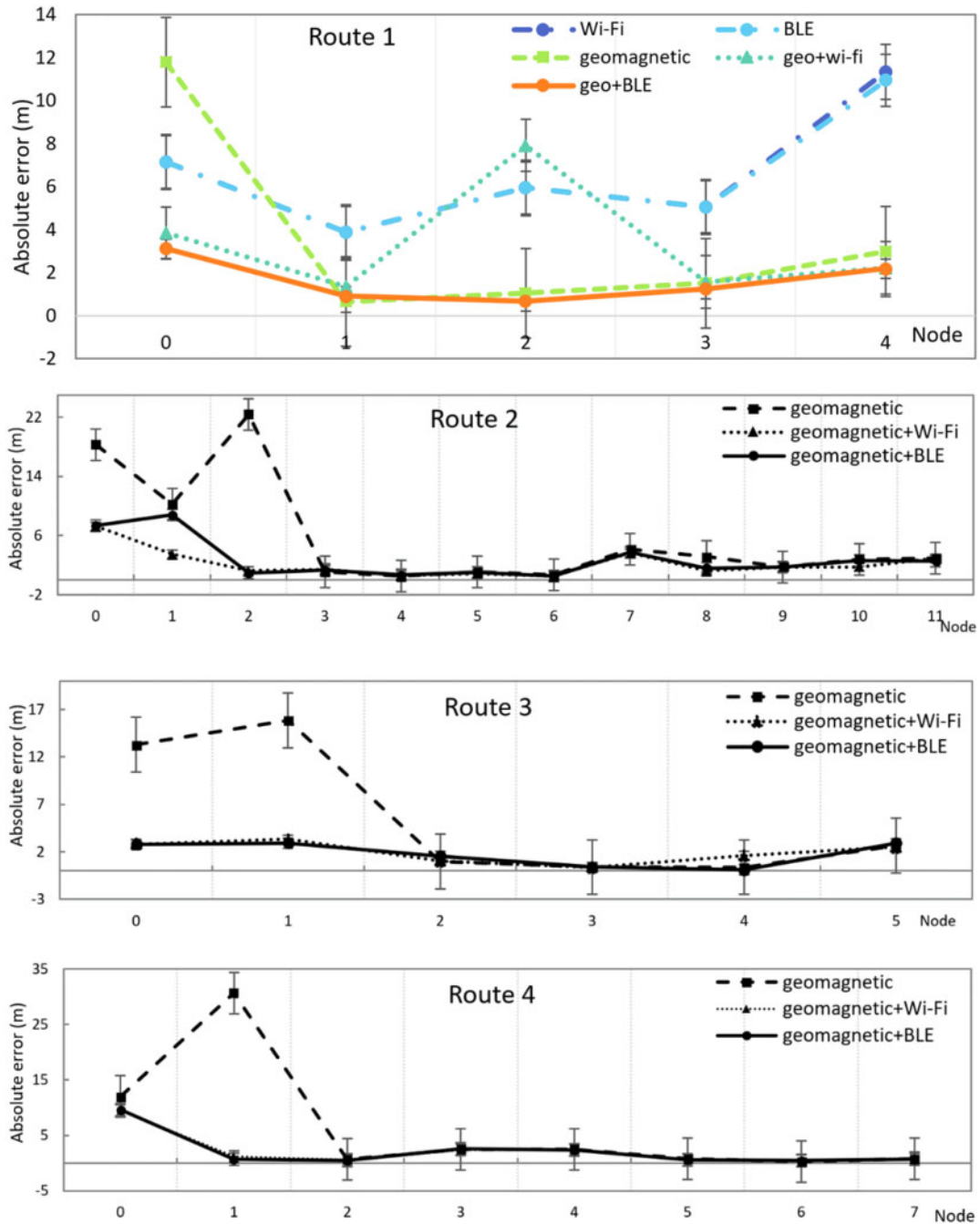


Figure 5. Absolute position errors for Experiment 1, Routes 1–8.

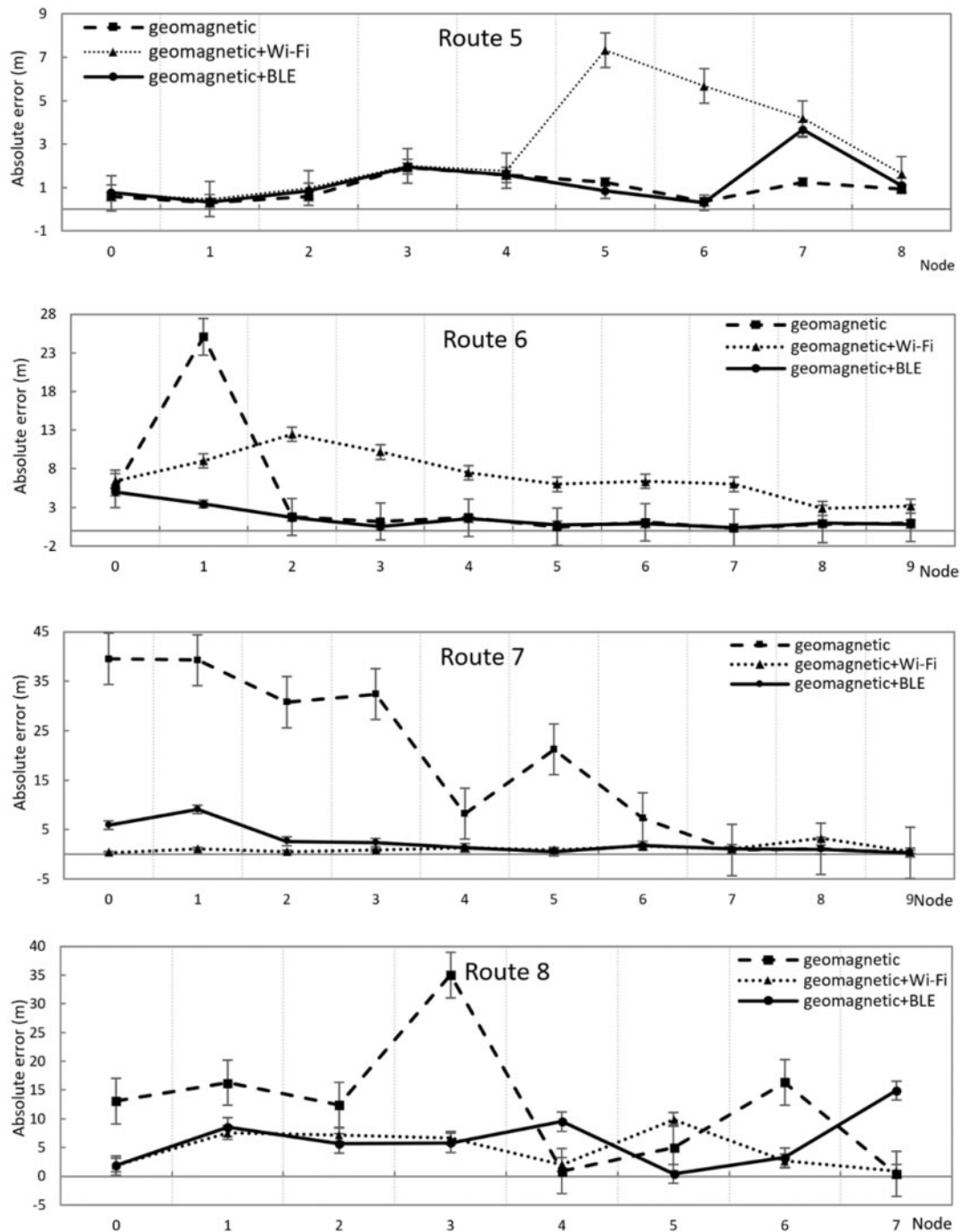


Figure 5. Continued

application included a predefined table listing the correspondences between barcodes and locations and included the location results in the database. The positioning accuracy was then evaluated by comparing the barcode-based information with the related smartphone logs.

Device orientation

In Experiment 1 (Section 2.1), the devices were held in a fixed orientation, but for Experiment 2 (Section 2.2), to more closely match real-world usage, users were not required to hold their devices in any fixed orientation. This was achieved using GiPStech's

“orientation free” feature, which calculates the device’s relative orientation and accordingly adapts the results, thus lifting the previous “fixed orientation” restriction.

RESULTS

Experiment 1: Accuracy of geomagnetic, Wi-Fi, and BLE beacon positioning

Figure 5 and Tables 2 and 3 show the average absolute position errors and standard deviations for Experiment 1, routes 1–8 (Figure 1) when

Table 2. Geomagnetic (GM), Wi-Fi, BLE, GM/Wi-Fi, and GM/BLE positioning errors, Route 1

Average error (m)			
GM (–)	NA	Wi-Fi	BLE
	–	6.68	6.60
GM (+)	3.61	3.39	1.63

using geomagnetic, Wi-Fi, BLE, geomagnetic/Wi-Fi, and geomagnetic/BLE positioning.

Experiment 2: Accuracy when combining geomagnetic and BLE beacon positioning

In room 808, the bar code was removed prior to verification, so positioning accuracy was not measured in this room and is not included in the average calculation. In addition, another room on the route was divided into a space for 4 people, but during the evaluation only 1 (typical) location was considered for that room.

Route 1: Professor's route when visiting all patients

The average position error for route 1 was 1.24 m (Figure 6a). This figure was established by reading barcode information when entering and leaving each room and within each room.

Route 2: Doctor's route when visiting all patients

The average position error for route 2 was 1.11 m (Figure 6b). This figure was established by reading barcode information when entering and leaving each room, within each room, and when entering and leaving the nurses' station.

Route 3: Nurses' typical route

The average position error for route 3 was 1.20 m (Figure 6c). This figure was established by reading barcode information when entering and leaving each room, within each room, and when entering and leaving the nurses' station.

DISCUSSION

Indoor positioning is very important for optimizing the provision of medical services, such as locating people and things, and understanding the occupancy level of medical wards and the usage status of medical devices. Wi-Fi has the problem of radio interference and the IMES method is costly and difficult to implement. Therefore, we believe that a positioning method that combines geomagnetic and BLE beacon information may be considered in the future.

After comparing the positioning accuracies of the geomagnetic, Wi-Fi, and BLE methods, we found that the average position error with the geomagnetic approach was 7.62 m, but this dropped to 3.19 m when combined with Wi-Fi information, and 2.60 m when combined with BLE beacons. Although the geomagnetic method suffered from variable positioning accuracy, this could be suppressed by combining it with Wi-Fi or BLE beacon information. From the past data, Wi-Fi positioning error is an average of several meters,¹³ and BLE positioning error is an average of 1 m to 5 m,¹⁴ and it is considered that geomagnetic positioning is excellent. From the results of our premeasurement under the same conditions, geomagnetic, Wi-Fi, and BLE alone had the best geomagnetic positioning accuracy of 3.61 m. The accuracy improved when combined with

Table 3. Geomagnetic (GM), GM/Wi-Fi, and GM/BLE positioning errors, Routes 2–8

Route	Average error (m)			Standard deviation (m)		
	GM	GM/Wi-Fi	GM/BLE	GM	GM/Wi-Fi	GM/BLE
2	5.74	2.20	2.72	7.03	1.82	2.55
3	5.58	1.93	1.76	6.43	1.03	1.18
4	6.28	2.25	2.21	9.90	2083	2.93
5	0.98	2.75	1.27	0.53	2.28	0.98
6	3.88	6.99	1.59	7.20	2.81	1.41
7	18.10	1.18	2.61	15.48	0.78	2.64
8	12.41	4.84	6.24	10.45	3.13	4.39

Table 4. Absolute position errors and standard deviations for Experiment 2, routes 1–3, for the combined geomagnetic and BLE beacon method

Route	Absolute error (m)			
	1	2	3	
Node	1	1.76	0.51	0.94
	2	1.31	1.00	0.68
	3	0.28	0.73	1.52
	4	0.74	1.39	0.52
	5	2.10	1.57	0.80
	6	0.72	0.70	1.24
	7	1.04	0.68	2.53
	8	2.25	0.87	0.91
	9	0.68	0.80	0.66
	10	0	1.69	1.41
	11	1.46	0.30	1.40
	12	0	1.68	1.55
	13	–	1.46	0.57
	14	–	0	0.90
	15	–	2.21	1.40
	16	–	0	0
	17	–	–	2.20
	18	–	–	0
Average error (m)		1.24	1.11	1.20
Standard deviation (m)		0.73	0.62	0.65

geomagnetic and Wi-Fi/BLE, and the positioning accuracy, especially when combined with BLE, was 1.63 m. Also, in our second experiment, the average positioning error with BLE was 3.85 m, but this dropped to 1.93 m when combining them with geomagnetic. Here again, we see that the geomagnetic method's variable positioning accuracy could be suppressed by combining it with the beacons. Also, since the 4-person room is 6 m square, the relatively high positioning error there (about 3 m per person) can be considered acceptable, especially for the typical use-case of understanding who is currently being treated.

For routes 2, 3, 4, and 8, it was necessary to specify the initial positions to achieve reasonable, stable accuracy results and the maximum position error was 22 m. We believe this is due to the characteristics of the PDR technology¹⁵ when using a particle filter algorithm. PDR positioning calculates the relative distance and direction from the starting point by measuring the user's movement with their smartphone's built-in sensors. Therefore, errors can

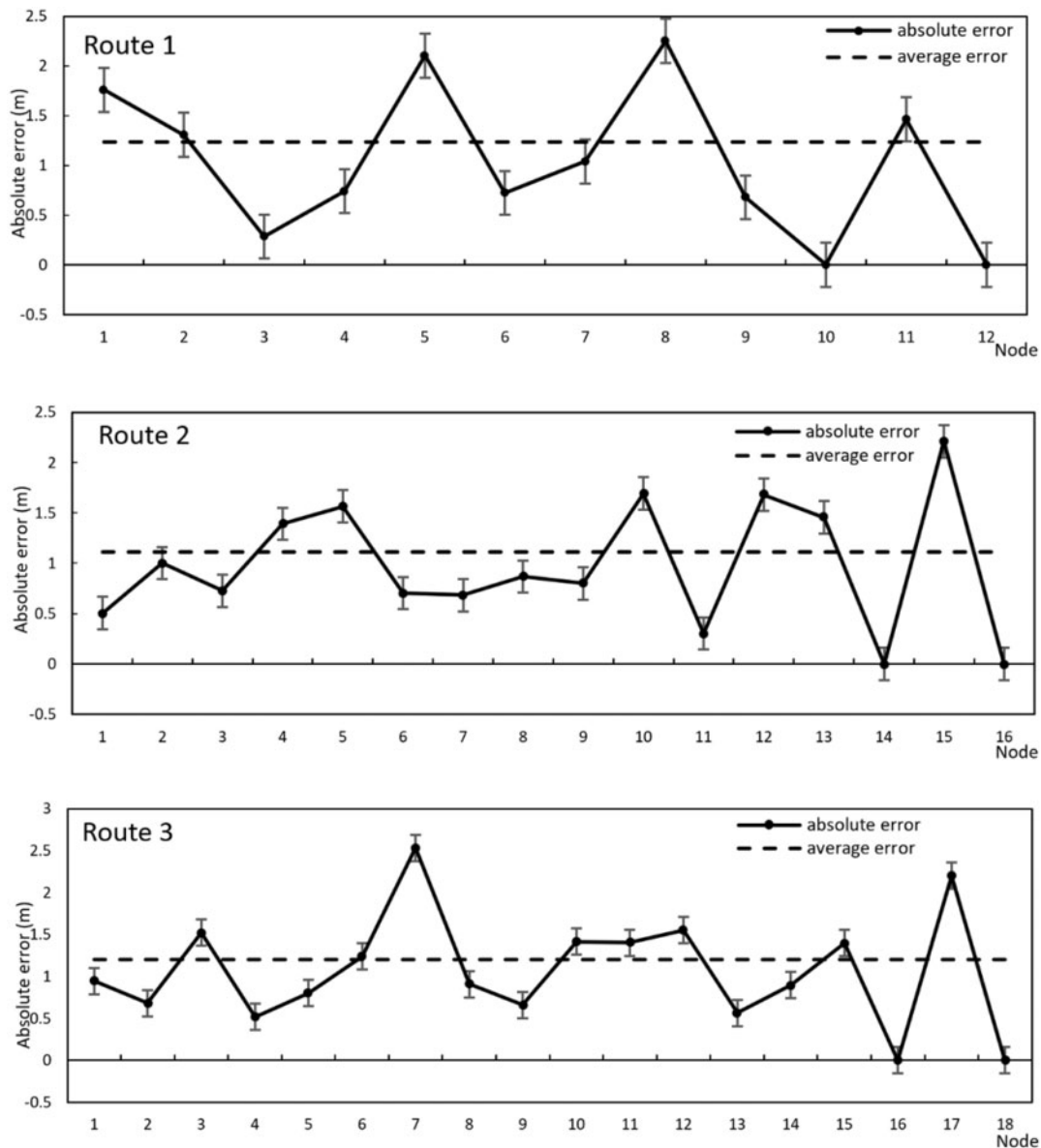


Figure 6. Absolute position errors and standard deviations for Experiment 2: a) Professor's route, b) Doctor's route, and c) Nurses' route.

accumulate over time, generating significant position differences. In our case, a significant factor was that the accuracy of the initial position was poor, due to the difficulty of finding a magnetic pattern, increasing the errors in the PDR position measurements. Moreover, since the positions become more stable over time with the help of an accurate initial position, the average position errors are smaller for longer routes.

The reason why the error in Route 5 was small is considered to be that when the magnetic field was measured, the magnetic fluctuation was small because there were almost no moving objects, and stable and highly accurate results were obtained. Here, it is thought that the accuracy of Wi-Fi is reduced due to radio interference.

For route 6, there was an object in the corridor during the experiment, which may have affected the geomagnetic and Wi-Fi positioning results. These were effectively corrected by the BLE beacon and the average error was reduced to 1.5 m. This shows that even in high-traffic hallways, combining geomagnetic and beacon data

makes it possible to obtain accurate measurements. With the same concerns, in fact, the test site environment had several metal containers, beds, and wheelchairs. However, unlike elevators, these metal items can pass close together without affecting the magnetic map or sensor if they are placed more than 10 cm apart.

Routes 7 and 8 went near an elevator, where the position error increased to 10 m. This was probably because the elevator is a large magnetic body that causes substantial fluctuations in the surrounding magnetic field.¹⁶ Another factor here could be the fact that many medical staff and patients were moving around in the vicinity while the measurements were being taken. We believe this issue could be improved by installing additional beacons near the elevator.

Examining the positioning log demonstrated that by combining the geomagnetic and BLE beacon approaches, we were able to accurately follow the preset routes. However, the route from the west to room 808 could not be followed accurately, and positioning was not stable in the hospital room. It is considered that this is because the

beacon installation position was not optimal. The beacons in the corridors and nurse stations were installed at a height of 2 m, and because it was difficult to install them on the wall inside the hospital room, they were installed on a 3 m high ceiling lighting fixture. Therefore, the positioning accuracy of the hospital room was not stable. This indicates that the positions are more stable when the beacon's height makes it easier to gain information about the movement of humans and goods.

For indoor positioning, the placement of beacons is important, so it is common to adjust the position and test the positioning accuracy several times, and, in some cases, it may be necessary to place many beacons at short intervals. In our experiments, we could only test 1 set of beacon placements, but we believe that careful consideration of beacon placement can improve accuracy.

The geomagnetic positioning method is expected to be utilized in the future. We believe it can be used to analyze nurse movements and suggest potential improvements in work practices. Hospital buildings contain many elements that can have a significant effect on the observed magnetic field, such as plumbing and communication cables, so interference creates a unique magnetic field structure that can be read from the magnetic field readings. Extracting spatial features is relatively easy. However, there are many other magnetic objects, such as steel trolleys and wheelchairs, so performing similar experiments in other facilities may give different results.

Our results have shown that positioning accuracy can be improved by combining geomagnetic positioning with BLE beacons. Particularly, we believe it could be effectively used to target people, such as patients or nurses, where we can tolerate position errors of about 2–3 m. Contrastingly, when targeting objects that must be located to an accuracy on the order of a few centimeters, such as medical equipment, it could be more effective to use devices such as a passive array antenna system (Quuppa) or ultra-wideband radio (Decawave).

We believe that, in the future, the hospital experience could be improved by combining location information (eg, for guidance and to aid navigation) with automatic hospital account payment systems.

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AUTHOR CONTRIBUTIONS

KY, SO, TO, SY, and TF developed the methods; DK, KS, SA, CF, NI, KM, and YS designed the study; KY, SO, and TO analyzed the data; and KY, and SO drafted the initial manuscript. All authors approved the manuscript to be published, and agree to be accountable for all aspects of the work, ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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CONFLICT OF INTEREST STATEMENT

None declared.

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