Visualisation and Avoidance of Uneven Road Surfaces for Wheelchair Users

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Abstract - The number of people aged 65 and above is increasing in Japan, and the ratio of wheelchair use of such people is higher than that of the younger generation. Hence, wheelchair use has been steadily increasing. Manual wheelchairs are most commonly used because they have more reasonable prices than electric-powered wheelchairs; however, they are also more restrictive. In addition, it is better if users can trace in a comfortable road surface. For this purpose, we can exploit the global positioning system (GPS) sensors, acceleration sensors and gyro sensors that have recently been embedded in smartphones. People can collect diverse data from smartphone sensors and share their knowledge through a network. This paper proposes a suggesting system to avoid tracing in an uncomfortable road surface by which wheelchair users can sense the road surface profile. This suggesting system senses uneven area of the roads by a three-axis acceleration sensor and a GPS sensor installed in a smartphone, which considerably reduces the cost. Because discomfort levels vary among users, we have developed a mapping solution which indicates a user's discomfort places by an interactive method on the smartphone. The system helps users mitigate uncomfortable reactions caused by passing through uneven roads in wheelchairs.

Keywords: probe information system, navigation system for wheelchairs, smartphone, wheelchairs, discomfort level

1 INTRODUCTION

Japan is entering a period of decreasing birth rate and ageing population. Consequently, wheelchair use is increasing and the wheelchair market has diversified. Electric-powered wheelchairs are currently evolving and gaining popularity. However, their cost renders them inaccessible to many people. Most schools, hospitals and department stores continue to use human-assisted models. These models provide on-site mobility; however, users who are unfamiliar with the site and are navigating a road for the first time may encounter problems. Therefore, we propose a navigation aid for wheelchair users, and evaluate its ability in a series of manual wheelchair experiments.

Miyazaki compared the social inaccessibility among walking persons, users of electric-powered wheelchairs and manual wheelchair users [1]. Contemporary lifestyle revolves around social activities such as working at the office, shopping, school lessons and receiving medical treatment at hospitals. Miyazaki's results are summarised in the comparison maps in his paper. These maps present the Tama Area outskirts of Tokyo. Miyazaki found that persons with impairments encounter various barriers to activities in the urban environment. In particular, users of manual wheelchairs have limited access to public facilities such as hospitals compared with walking persons and people using electric-powered wheelchairs.

Even when access itself is not problematic, travelling down the street may be uncomfortable for wheelchair users.

Able persons cannot imagine the impact of road conditions on wheelchair users. Even on flat surfaces, wheelchairs are sensitive to the texture of the road. Because they are used for directional steering, the front wheels of typical wheelchairs are tubeless with a small diameter (not larger than 7 inches) [2]. However, this design increases the sensitivity to the road surface conditions. A small-diameter solid tyre greatly senses the surface irregularities.

By visualising the discomfort level of the road surface, users can navigate their wheelchairs to avoid these courses.

The discomfort level of wheelchair vibrations relates to not only the surface conditions but also the speed of the wheelchair and the weight of the user. Steep and sudden slopes pose additional dangers to wheelchair users as the speed of the wheelchair becomes harder to control. When users decelerate while approaching a bad road condition, they can mitigate their discomfort level. In outdoor environments, GPS sensors on smartphones can detect the user's position on the road. If the sidewalk is sufficiently wide, the conditions can differ on the same road. For this purpose, the precision of the GPS sensors must reach 1 m.

As micro electric mechanical system (MEMS) technology becomes more widespread, more smartphones are being installed with sensor technologies. Since 2000, MEMS technology has been incorporated in automotive acceleration sensors which detect a sudden deceleration to enable airbags, gyro sensors which guide drivers along safe routes and reduce hand vibrations when pushing digital camera buttons, and many other systems. The field of mobile sensing has greatly advanced in recent years; many studies have focused on incorporating such sensors in cars, bikes, bicycles and wheelchairs. Moreover, the number of smartphone users is increasing dramatically, and acceleration and gyro sensors are increasingly used for logging long-term data. With these tools, users can gather information on their circumstances and share that information among interested parties. Using their smartphones, people can develop a cost-effective, convenient networking system based on the embedded sensor technology. This study addresses the installation of three-axis acceleration sensors and GPS sensors on the smartphone, which detect bad road conditions, which would increase wheelchair vibration.

Our method detects uneven road surfaces that convey unpleasant vibrations to wheelchair users. The individual discomfort levels of users are determined by an interactive input method. Based on this input, the system indicates the potential discomfort zones on the road.

2 RELATED WORK

To the best of our knowledge, there are at least four related papers on navigation systems for wheelchair users. One system uses acceleration sensors on a smartphone; the others retrieve the logs from commercial three-axis accelerometers.

2.1 Indoor and Outdoor Navigation System for Disabled Persons

In 2012, Nattapob et al. created a navigation system based on static information, such as stairways and precipitous slopes [3]. The smartphone obtains values from a direction sensor and communicates to a wheel speed sensor through Bluetooth. However, this method is not designed for sharp drops in road level (Fig. 1), sidewalks under construction (Fig. 2), sections of old pavements (Fig. 3), or similar conditions which increase the discomfort of wheelchair users. Therefore, Nattapob's system cannot detect the discomfort level of a road surface [3].

2.2 Unevenness Evaluation of Sidewalk Pavement by Vibrational Acceleration of Wheelchair

In 2004, Okamura and colleagues demonstrated that the surface of a paved sidewalk causes undesired vibration, which may physically harm the human body [4]. Moreover, the vibrational acceleration is proportional to the travel speed. They found that a surface similar to that illustrated in Fig. 4 can be traversed by wheelchair users for one hour per day without causing side-effects. An example of such a sidewalk is photographed in Fig. 5 [4] - [6].

Okamura's group reported the following four findings.

1) The dominant frequency of the acceleration response to wheelchair vibration of the wheelchair is a near-integer multiple of the space size between the joints.

2) The magnitude of the acceleration is proportional to the speed of the wheelchair and is most marked in the vertical direction.

3) Lighter persons experience more vibration than their heavier counterparts.

4) The measured vibrational acceleration indicates the discomfort level of the vibration.

2.3 Spatiotemporal Life-log Mining of Wheelchair Driving for Visualising Road Accessibility

In 2013, Iwasawa's group tested the ability of three-axis accelerometers to capture the surface road conditions [8]. They classified the road surface as rough and smooth and displayed the results in the comparison maps between actual and estimated statuses of the ground surface.

However, the accelerators used in this study were not smartphone-based. Moreover, the study objectives were to visualise the road accessibility, not determine the comfort level of the road surface [7] [8].

Although these authors theoretically evaluated the comfort level of wheelchair users by the VAL (vibration acceleration level), we consider that discomfort levels should be alleviated by human interaction, as they depend on the individual sensibilities of users.

Figure 1: Sharp drop in the road level

Figure 2: Sidewalk under construction

Figure 3: Old pavement on a sidewalk

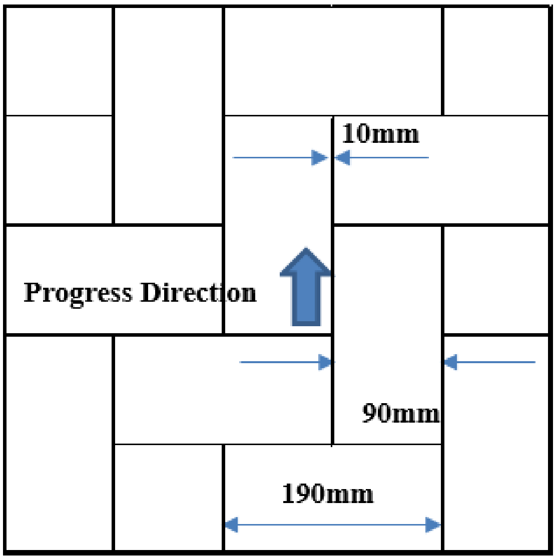

Figure 4: Uneven surface conditions on a paved sidewalk with tiles

Figure 5: Sidewalk paved with tiles

2.4 Determining the Discomfort Level from Inertia and Human Body Information of Wheelchair Users

In 2015, Isezaki and colleagues presumed the discomfort level from the body information of electric-powered wheelchair users [9]. They used a smartphone-based acceleration sensor and a biometric sensor which detects electric signals from the heart. However, they tested their system on an indoor walkway with and without a sharp drop, without varying the height of the drop. Their presumed discomfort level did not account for individual diversities.

Table 1: Advantages and disadvantages of related work

	surface condition on the road	Sensor on the Smatrtphone
2.1 Navigation	No	No
2.2 Evaluation	Yes	No
2.3 Visualization	Yes	No
2.4 Presumption	Yes	Yes

2.5 Summary of Related Work

Table 1 summarizes the advantages and disadvantages of the related work mentioned in this section.

Nattapob et al.'s method does not sense the road surface, which determines the discomfort level of the vibration. Okamura's group evaluated the vibrational damage, but their method requires accelerometers specific to this purpose. Iwasawa et al.'s approach is limited by a similar specificity; moreover, it targets the road rather than users' discomfort

levels. Although Isezaki et al. adopted a smartphone-based approach, the acceleration and biometric sensors presume the discomfort level of electric-powered wheelchair users.

The method is unsuitable for manual wheelchair evaluation because manual wheelchairs introduce noise in the biometric sensor.

Given these limitations, we propose a low-cost method that precisely senses individual discomfort levels imparted by the road surface. The information is provided by smartphone sensors. The user determines the threshold acceleration beyond which he or she would feel uncomfortable while driving the wheelchair. The proposed method then proactively displays the potential discomfort sites on the road.

3 PROPOSED METHOD

This section details the study purpose and approach, and explains how our proposed system solves the problems in related papers.

3.1 Purpose and Approach

Problems with existing approaches include high introductory cost, and inability to detect individual differences in discomfort levels.

Our proposed system collects information at reasonable cost by a three-axis accelerometer and a GPS sensor installed on a smartphone. The discomfort imparted to the user by the road surface and the GPS position of the uneven surface is conveyed by an interactive method. Moreover, because the discomfort level is user-specified, the system assesses individual discomfort levels from the vibrational acceleration.

This study aims to collect the acceleration values on bumpy road surfaces and display the badly conditioned regions of the sidewalk on the map. The final target of this study is a navigation system by which wheelchair users can avoid uncomfortable routes in their future travels.

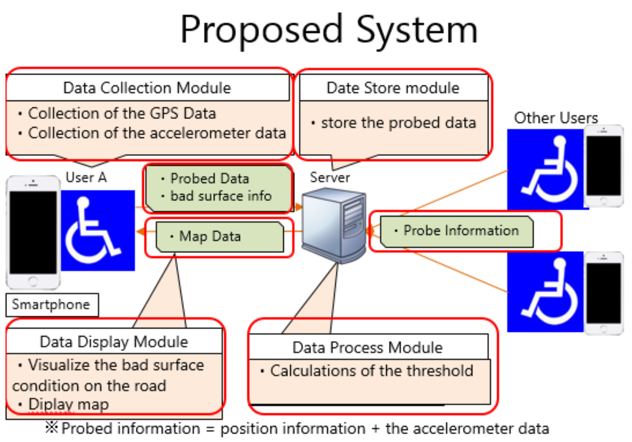

Figure 6: Modules of the proposed system

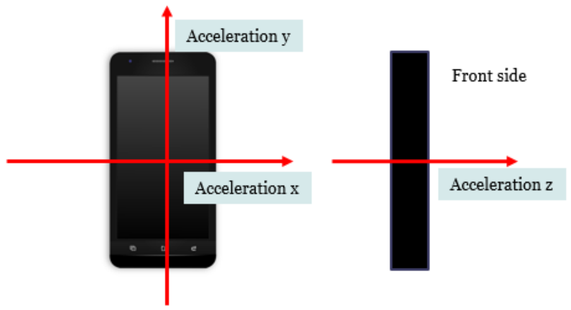

Figure 7: Acceleration components of the smartphone

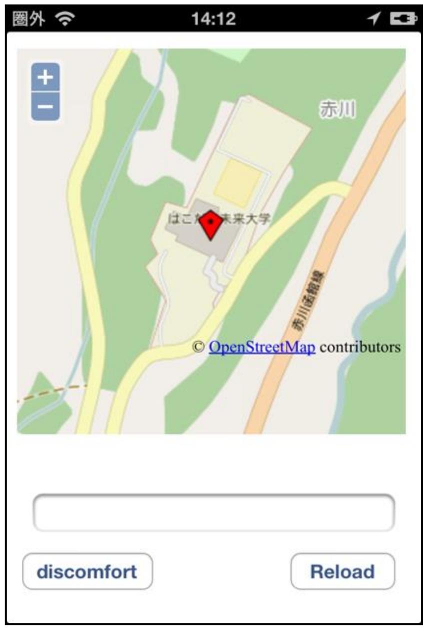

Figure 8: Data collection user interface on the smartphone

Table 2: Records sent to the server

UserID	ID of each user
Latitude	Value from GPS
Longitude	Value from GPS
Acceleration Y	Value from Accelerometer

3.2 Overview of the Proposed System

The proposed system comprises four components (Fig. 6). The interactive input method identifies a user's individual discomfort level from historical data. The first module is the data collection module, which is installed on the smartphone. This module collects the sensed data from the three-axis accelerometers and the GPS sensors on the smartphone. The second module (the data processing module) operates on the server and calculates the discomfort threshold based on the gathered data. The third module is the data storage module, which receives data from the smartphone. This module also operates on the server. The fourth module (the data display module) presents the existing uneven road surfaces, on which the user's discomfort level is likely to exceed the threshold. This information is presented on the smartphone map.

3.3 Visualising the Discomfort Site of the Road

In this subsection, we describe how our proposed method visualises the uneven road surfaces. The acceleration components of the smartphone are measured as indicated in Fig. 7. Once the unique ID is input to the system, the proposed system will store and calculate the threshold discomfort levels of the wheelchair user.

3.3.1 At the Start of Moving

The information is retrieved by an iPhone4 affixed to the left arm of the wheelchair. Data collection begins shortly after the user enters his or her unique ID into the smartphone screen (Fig. 8) and continues for 60 s. At 60-s intervals, the data are sent to the server, along with the records displayed in Table 2.

3.3.2 Data Collection

Each second, the smartphone acquires the latitude and longitude from the GPS sensor and the maximum and minimum accelerations in the y direction from the three-axis accelerometer.

If the user experiences uncomfortable vibrations, he or she pushes the button on the screen of the smartphone. If the discomfort level is being tracked for the first time, that level will be stored in the database and assumed as the Min/Max threshold value (Fig. 9).

If the discomfort level has been previously tracked, it is stored after calculating the average value of the current and historical values, as shown in Fig. 10.

Table 3 lists the values that define a user's discomfort profile. These values are stored in the database.

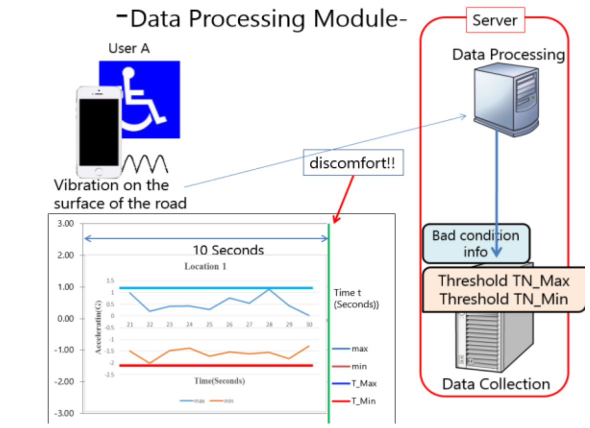

Figure 9: Data collection during first-time tracking

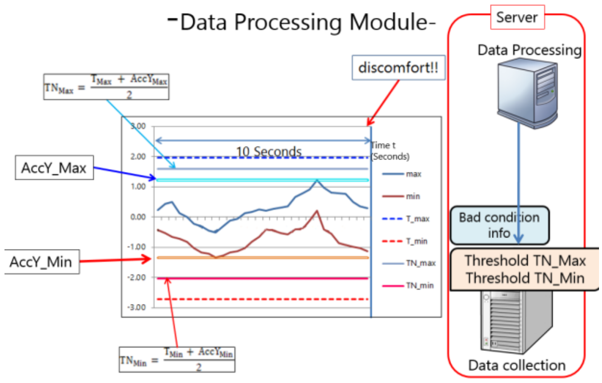

Figure 10: Data collection after multiple tracking

Table 3: Records stored in the database

UserID	ID of each user
Latitude	Value from GPS
Longitude	Value from GPS
Acceleration Y	Value from Accelerometer
Threshold max	Max threshold value of each user
Threshold min	Min threshold valu of each user
Comfort	information that feels discomfort

3.3.3 Data Display

The system stores the values in the database and displays the information on the smartphone screen, as shown in Fig. 11. If the user's threshold is below that of multiple users in the same area, the map highlightsthe potential discomfort sites. The display API is OpenStreetMapAPI.

4 EXPERIMENTS AND DISCUSSION

In this section, we explain the experiments and simulation we conducted to confirm the effectiveness of the proposed method and discuss the results.

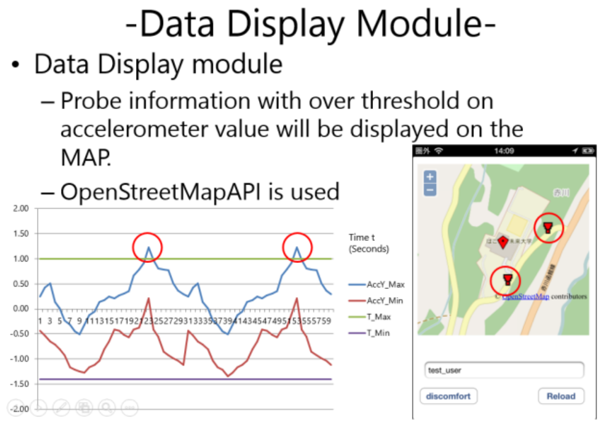

Figure 11: Data display on the smartphone screen

Figure 12: Experimental environment

4.1 Experiments

We conducted two experiments. The first experiment was conducted inside the room and the second was conducted outside the building.

4.1.1 Experiment 1

Before creating the proposed method, we investigated the relationship between wheelchair vibrations and the road surface conditions. We found that the front tube-less tyre is sensitive to the surface unevenness. To assess the accuracy of sensing the road surface profile from the uncomfortable vibration level of the wheelchair users, we conducted the following tests.

(1) The smartphone was affixed to the left arm of the wheelchair. Data were collected by a HASC Tool [10] as shown in Fig. 12. Kawaguchi et al. organized a consortium-called 'HASC: Human Activity Sensing Consortium', and started a collaborative project for gathering a large scale human activity corpus. HASC Tool is a corpus tool, and its basic function was used. A schematic of the testing board, showing the varying spacing between several bars, is presented in Fig. 13. Each bar was 2 or 4 mm high. This experiment was called Experiment 1.

(2) We employed a common wheelchair with a 7-inch front tyre and a 24-inch rear tyre.

(3) We trialled 4 different patterns of the testing board.

(4) Each pattern was tested 5 times by 5 persons (yielding 200 trials: 4 patterns × 2 heights × 5 times × 5 persons).

(5) The test subjects were five students with different weights (55 kg, 58 kg, 64 kg, 65 kg and 73 kg).

In Experiment 1, the smartphone fixed on the left arm of the wheelchair detected the vibrations from the uneven testing board in the indoor environment. The testing board was designed to be detected from the ground by the front tubeless tyre of the wheelchair. The aim was to reveal the extent to which the smartphone's accelerometer can detect the surface profile from the vertical vibrational acceleration *y*. As revealed in the initial raw data, the surface signal was not precisely determined in this test (Fig. 14).

Noises in the accelerometer readings could be filtered by four periods of moving average. Figure 15 shows the acceleration profile after the filtering. Many of the noises in Fig. 14 were successfully eliminated by the filtering. A simplified graph is presented in Fig. 16. In almost all of the 200 trials, the exact space-size differences between the bars along the test board were derived from the acceleration sensor of the smartphone.

4.1.2 Experiment 2

After performing experiment 1, we gathered simulation data and verified the effectiveness of the proposed method. To sense the wheelchair's vibration from the real surface of the road, outdoor tests (experiment 2) were conducted from the front door of the university to the bus stop (Fig. 17). The five subjects made a round trip.

In Experiment 2, testers navigated the wheelchair along the road outside the university. Wheelchairs equipped with smartphones collected the acceleration and GPS values from the entrance to the bus-stop, along the route shown in Fig. 17. To identify whether the system could identify actual environmental features such as hearing the user's voice and perceiving the surface status of the road (smooth or rough), the test team followed the wheelchair users while taking a movie on a different smartphone.

The effectiveness of the method was evaluated in a simulation study based on Experiment 2.

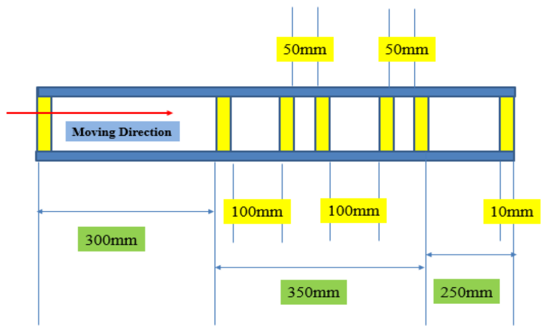

Figure 13: Schematic of the testing board with an uneven surface

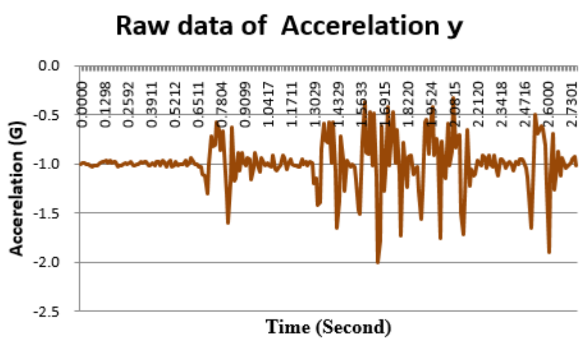

Figure 14: Raw data of vertical acceleration *y*

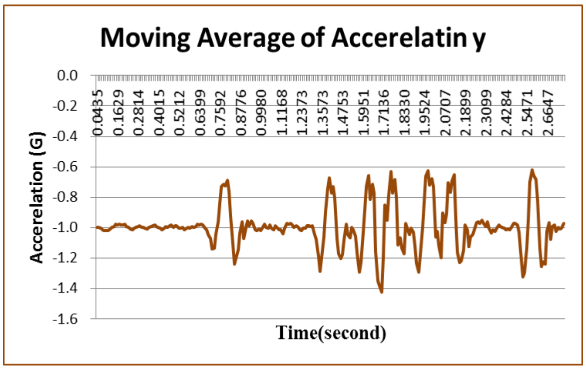

Figure 15: Moving average of vertical acceleration *y*

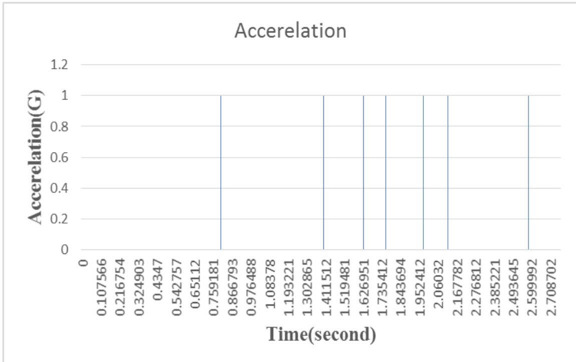

Figure 16: Simplified graph of vertical acceleration *y*

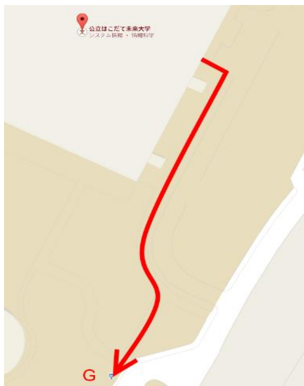

Figure 17: Experimental route from university entrance to bus stop

4.1.3 Results of Interview for Experiments

After conducting experiments 1 and 2, we surveyed each subject to evaluate the relationship between wheelchair vibrations and each individual wheelchair user's discomfort level.

Table 4 displays the format of a survey administered to the 5 testers. The testers rated three categories 'comfort', 'restfulness' and 'stability' on one of seven levels (extremely negative, moderately negative, slightly negative, neutral, slightly positive, moderately positive and extremely positive).

The responses were analysed by principal component analysis (PCA) [11]. PCA is a useful statistical technique that has found application in fields such as face recognition and image compression, and it is a common technique for determining patterns in high-dimension data. In the first analysis, we integrated comfort and restfulness into a measure of comfortability when using the wheelchair. In the second analysis, we integrated restfulness and stability into a measure of user safety. A scatter diagram of the analysis is plotted in Fig. 18. The levels of comfort and safety differed among the testers, although all testers moved along the same conditional testing boards and outdoor route.

4.2 Simulation Results

We performed simulation using data from experiment 2 to verify the effectiveness of the proposed method. We acquired logging data from the university entrance to the bus stop on the acceleration and GPS sensors embedded into the smartphone.

The wheelchair users encountered uneven sites at 27 s (no.1 in Fig. 19), 45 s (no.2 in Fig. 19) and 57 s (no.3 in Fig. 19) from the start of the route (university entrance). We then simulated this situation and determined the locations of the bumpy sites from the simulation results.

The tracking movie captured on the smartphone easily distinguished the regions of the bumpy sidewalk. An example is shown in Fig. 20.

From the wheelchair log data, we constructed the acceleration–time profile and identified the minimum and maximum accelerations.

The profiles around the first, second and third uneven sites are presented as Fig. 21, Fig. 22 and Fig. 23, respectively. The identified maximum and minimum values were selected as the threshold discomfort levels of the wheelchair's vibration.

Table 5 shows the *y* acceleration values stored by the smartphone. The discomfort level of the road surface was displayed on the smartphone screen.

4.3 Discussion of Experimental and Simulation Results

This subsection discusses the experimental and simulation results. The two experiments yielded the following findings. In experiment 1, in 200 trials, the signals of the testing boards were detected with an almost 100% success rate.

Table 4: Format of the interview

Please mark your responses on the survey								
1. discomfort	extremely negative	moderately negative	slightly negativ	neutral	slightly positive	moderately positive	extremely positive	1.comfort
2. restless	extremely negative	moderately negative	slightly negativ	neutral	slightly positive	moderately positive	extremely positive	2.restful
3. unstable	extremely negative	moderately negative	slightly negativ	neutral	slightly positive	moderately positive	extremely positive	3.stable

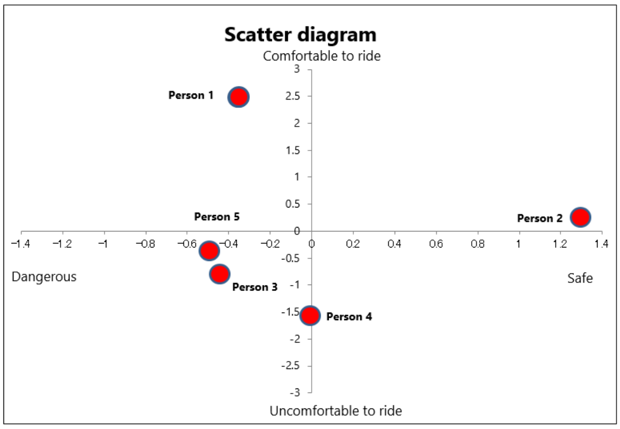

Figure 18: Scatter diagram of the principal component analysis

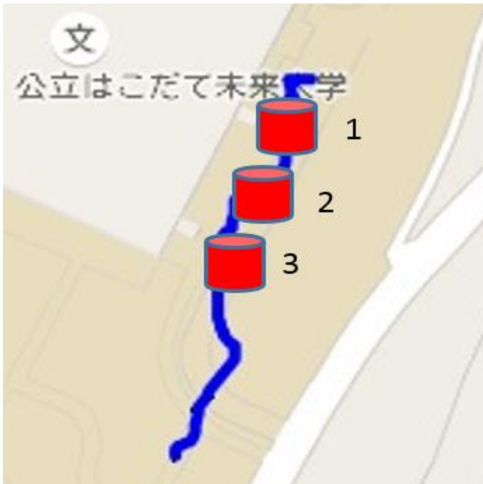

Figure 19: Experimental route from university entrance to bus stop, showing uneven sites

Figure 20: Example of a bumpy sidewalk

Hence, we could see that the wheelchair's vibration has a strong association with the surface profile of the road.

In experiment 2, we obtained accurate vibration and GPS data. This shows the effectiveness of the map as the output of the data displayed the potential discomfort location. The

Figure 21: MAX/MIN accelerations at the first uneven site along the outdoor route

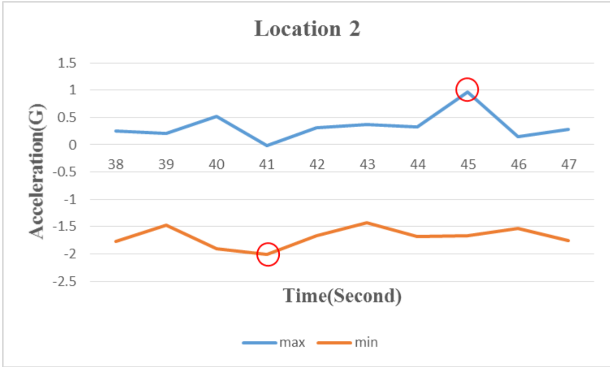

Figure 22: MAX/MIN accelerations at the second uneven site along the outdoor route

scatter diagram of interviews and tracking movies of experiment 2 showed that the comfort levels of wheelchair users are highly individual specific. Therefore, the vibration level deemed as uncomfortable cannot be standardised. Our simulation with the experiment 2 data showed the effectiveness of visualizing the potential discomfort levels for wheelchair users on the smartphone map using a sensor embedded into the smartphone.

Compared with existing methods, our method has several advantages. Existing studies of wheelchair navigation are beset by several problems. In particular, both the acceleration and GPS data must be obtained at reasonable costs, and the discomfort level derived from acceleration values is highly individualistic. Our proposed method addresses these issues.

However, there are other factors that have an influence on the discomfort level of wheelchairs are undetectable by acceleration and GPS data. One of the factors is sharp slopes. Without vibration, sharp slopes could be a hindrance to wheelchair users. Note that the current work does not address this issue.

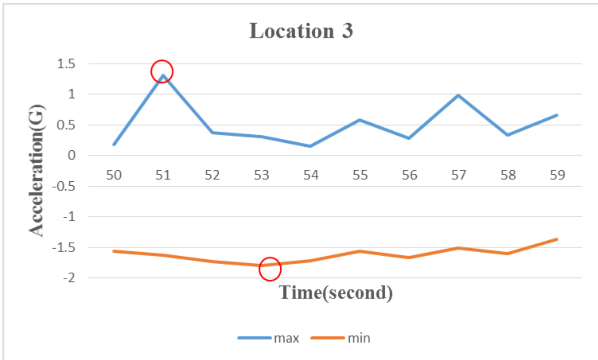

Figure 23: MAX/MIN accelerations at the third uneven site along the outdoor route

Table 5: Stored MIN/MAX accelerations reported as the thresholds

	Real Value		Threshold (after calcultion)	
	Acc Y min (G)	Acc Y max (G)	Acc Y min (G)	Acc Y max (G)
Location1	−2.0084475	1.14548875	−2.0084475	1.14548875
Location2	−2.007637	0.96374525	−2.00804225	1.054617
Location3	−1.79909875	1.038414	−1.9035705	1.0465155

5 CONCLUSIONS

In this study, we proposed a method for visualization and avoidance of uneven road surfaces for manual wheelchair users using smartphones with an embedded acceleration sensor and a GPS sensor. We implemented the system of the proposed method and conducted experiments and simulation to confirm its effectiveness.

We proposed a method displaying potentially uncomfortable zones as surface information on the road map of the smartphone. Because every trigger is initiated by the wheelchair user, this system will provide individual assistance.

In future work, the system must be evaluated on a real sidewalk. We will also create a navigation system to evaluate the effectiveness of the method.

At present, our method relies on the wheelchair users' own activities. Ideally, we should find a proactive measure, by which probe-wheelchairs could check the road status before the road is accessed by many users. For a more realistic navigation, we also need to identify the slope by gyro sensors and consider the scalability of the servers and collectiveness of the probed data.

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