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Estimation of Wheelchair States during Movement Using WELL-SphERE for Evaluation of Power Wheelchair Safety*

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Abstract— **To comprehensively evaluate the usability and safety of a power wheelchair (PWC), monitoring multimodal data related to the PWC in a real environment is crucial. In most studies exploring actual wheelchair conditions, modification of PWCs has been required. Especially modification of controlling circuits aiming for measurement of joystick operation may lead to controller malfunction and thus increase safety risk. It is essential, therefore, to ensure the safety of PWC users during experiments so that they can measure PWC-related data with their own wheelchairs. To achieve this aim, we developed a recording device that is easily installed on PWCs without any electronic modifications. The device, called a "WELL-SphERE," has sensing units that can be attached to PWCs a data management unit that can store and transfer measurement data. Here, we focused on joystick operation logged by the system. Seven participants were pre-tested to examine the characteristics of logged operations during runs through four test courses. Subsequently, all participants completed a questionnaire regarding the difficulty of the test courses. From these results, we classified the logged operations into four categories of "wheelchair states." Two participants—a novice driver and a mature driver—were also evaluated to verify the accuracy of the estimated wheelchair states. The accuracies of the estimates by the mature and novice driver were 98.8% and 89.0%, respectively. The wheelchair states for both participants showed characteristic patterns. Therefore, the wheelchair states estimated with the data logged using WELL-SphERE are valid indicators of the wheelchair conditions during movement.**

I. Introduction

Maintaining an operational log in a real environment is useful for determining the usability and safety of power wheelchairs (PWCs) [1, 2]. There are many dangerous locations for PWC users, such as rough roads, side slopes, and narrow roads. Identifying these locations is important in examining the safety of PWC users. A number of studies have been conducted to investigate road conditions by using accelerometers attached to PWCs. In most studies exploring actual wheelchair conditions, intensive modification and/or customization of PWCs has been required. These devices are suitable for an indoor or experimental environments, but unsuitable for real environments because it is difficult to compel the PWC users to master how to use the customized wheelchair. Ensuring the safety of PWC users during experiments is crucial for users to measure PWC-related data with their own wheelchairs. Therefore, we developed a recording device that is easily attached to the PWC without any modifications. We named the device "WELL-SphERE" after the initials for "Wheelchair Everyday Life Log with Smartphone-based Electronic Recording Equipment."

In this study, we focused on joystick operations logged by the system because we hypothesized that the condition of the driver, such as his/her feelings, thoughts, and carefulness are reflected in the logged operations. That is to say, the information of logged operations would show the dangerous locations and situations, so the life log is useful for evaluation of PWC users' safety.

The final goal of this study is to examine PWC users' safety in a real environment by logged operations. In this study, we tried to examine the feasibility test and characterization of the developed system "WELL-SphERE". Healthy participants were recruited for evaluating our system. We developed the scale of the driver's condition "wheelchair states" during move. The scales are calculated from the log of joystick angle. Hence, we used a modified PWC to determine the accuracy of estimated wheelchair state. The modified PWC used in the experiments can directly output a voltage that corresponds to the joystick angle.

II. Methods

A. WELL-SphERE system

We developed a device to record and manage multimodal data related to a wheelchair in a real environment. The "WELL-SphERE" device has two main components: a data collection unit and a data management unit, as shown in Figure 1(a). The arrows show the flow of data; the red and blue arrows are wireless and wired connections, respectively. The collection unit consists of an A/D converter unit with many input ports, and the data management unit is an android OS smart-phone that stores sensor signals and GPS position data. The sensor signals are stored in the SD card when the smart-phone is in a non-communicable area; otherwise, the user can decide to store the measured data on the smart-phone SD card or on the data server on the Internet. Therefore, once the WELL-SphERE system is mounted onto a to-be-measured wheelchair, researchers can easily collect measurement data from a server via the Internet without going to a location of interest. Figure 1(b) shows the experimental setup. Two triaxial accelerometers were mounted on and around the joystick to estimate the angle of the joystick operations.

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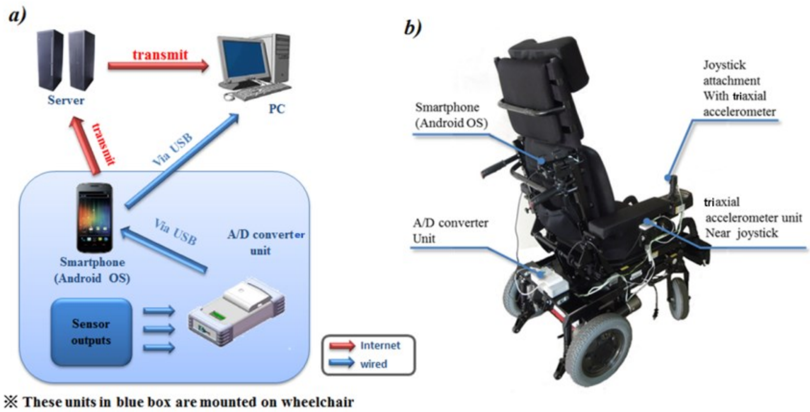

Figure 1. a) Schematic diagram of WELL-SphERE system and b) device setup. The system consists of two main components: the collection unit (A/D converter unit) and the data management unit (smart-phone and server). In a), each arrow indicates a connection between components; the red and blue arrows indicate wireless and wired connections, respectively. Measurement data are readily collected from a data server via the Internet. b) Power wheelchair equipped with WELL-SphERE system and modified joystick circuit. Two triaxial accelerometers are set up a top the joystick and on the wheelchair near the joystick. The system battery inside the A/D converter unit powers the smart-phone.

One was set in a custom-designed cap-like attachment that was placed on the tip of the joystick and held there by six set screws to prevent its removal from the joystick. The other was mounted near the joystick to detect acceleration of the PWC. The accelerometers were identical (AS-3ACC-3, Asakusa Giken) with a measurable range of ±1.5 g.

To examine the accuracy of joystick angles estimated by WELL-Sphere system, a controlling circuit of the test PWC was modified as follows. The joystick circuit has rotary encoders that can measure operating angle of joystick in front-back and lateral directions, respectively. The rotary encoder circuit was modified to output the voltage corresponding to the tilt angle of the controller. The voltage signals constitute a log of the actual joystick operations. The accelerometer and voltage signals were simultaneously sampled at 25 Hz by the A/D converter unit.

B. Pre-test

The purpose of this test is to examine the characteristics of the operation log while the driver runs through easy and difficult courses. We hypothesized that drivers would show characteristic patterns of joystick operation when experiencing fear in a dangerous situation. If the drivers fear that they are about to crash against the wall or a corn, the logged operations might show characteristic patterns such as stopping or marginal operation indicative of carefulness, or rapid switching operations that reflect impatience.

The seven participants that were evaluated in the pre-test consisted of three males and four females, ranging from 18 to 42 years old. All tests were performed after obtaining informed consent. The pre-test courses are shown in Figure 2. Participants were asked to run through four courses: the right turn, left turn, turn round, and slalom courses. After the tests, all participants completed a questionnaire on which course they considered the most difficult or easiest to examine a relationship between the characteristic pattern of logged operation and driver's feelings.

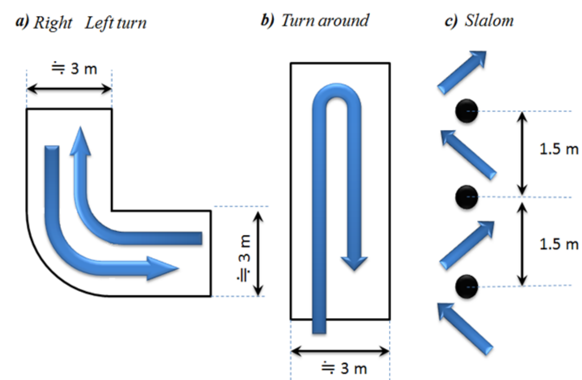

Figure 2. Pre-test courses to confirm difficult and easy courses for drivers. a) Course that requires drivers to turn right or left. b) Course that requires drivers to turn round. c) Slalom course.

C. Evaluation test

The purpose of this test is to verify the accuracy of estimated wheelchair states. In the case of actual use in a real environment, the personal PWC of a user should be used. Therefore, only the signals from the accelerometer attached to the tip of the joystick can be used for estimating the wheelchair state. The wheelchair state is calculated from the operational angle of the joystick. First, the operational angle of the joystick operations was estimated. The estimated angle of logged operations was calculated by subtracting the acceleration signal of the accelerometer mounted near the joystick from that of the accelerometer mounted onto the tip of the joystick. Subsequently, the subtracted acceleration was filtered by a simple moving average to remove the noise [3]. Then, the wheelchair state was determined based on the distance from the estimated angle, but Area1 and Area2 are divided by a linear line that is a same value both the tilt angle in front-back direction and the tilt angle in right-left direction. (in Figure 3, D is the distance of the joystick position at the angle of operation from the home position).

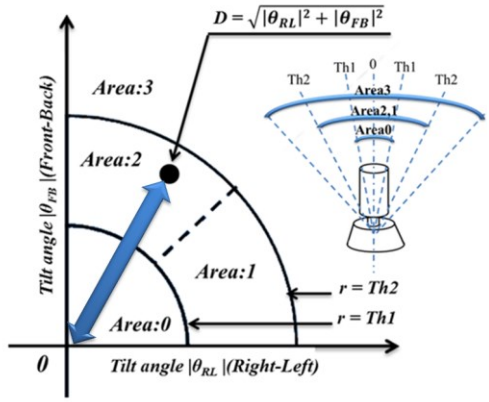

Figure 3. Wheelchair states estimated from joystick operation. There are four areas: The wheelchair maintains a stopped or slightly moving state when the operational state is in Area 0. In Areas 1and 2, the wheelchair moves slowly. In Area 3, the wheelchair moves rapidly without carefulness on the part of the driver. The drawing on the right shows the relationship between the operational state and the operational joystick log.

Two participants given the evaluation test were asked to run through the test course shown in Figure 5 with a modified PWC on which a WELL-SphERE system was mounted. Participant B was a novice at using the PWC, whereas, in comparison, participant A was an experienced driver. In this regard, both of Paticipants A and B are healthy subjects. The evaluation test course was approximately 230 m and had an angular slope of 3.5°. The accuracy of estimated wheelchair state is calculated by comparison between estimated wheelchair state calculated by the accelerometer signals and actual wheelchair state calculated by the rotary encoder signals.

III. Results and Discussion

According to the results of the questionnaire, all participants chose the slalom course as the most difficult. Some participants chose the turn course as the easiest course, whereas others chose the turn round course. There is no bilateral difference in the results of questionnaire. Moreover, we can easy to identify which operations were done in lateral direction if we have a GPS position data. Additionally, there were very few reverse operation logs overall. Therefore, we examined the distribution of the absolute number of operational angles, as shown in Figure 3. The distribution of logged operations in the first quadrant was divided into four areas that defined "wheelchair states," where Th1 and Th2 are the threshold levels. In Area 0, which ranged from the original point of the joystick to Th1, the wheelchair is in a stopped or slightly moving state. In Areas 1 and 2, which ranged from Th1 to Th2, the wheelchair is slowly moving carefully. The difference between Areas 1 and 2 is the direction of movement, where the PWC moves straight in Area 2 whereas it changes direction in Area 1. Area 3, which is beyond Th2, indicates that the wheelchair is moving rapidly. The Area number indicates the degree of carefulness during an operation (Area 0 > Area 1 > Area 2 > Area 3) as

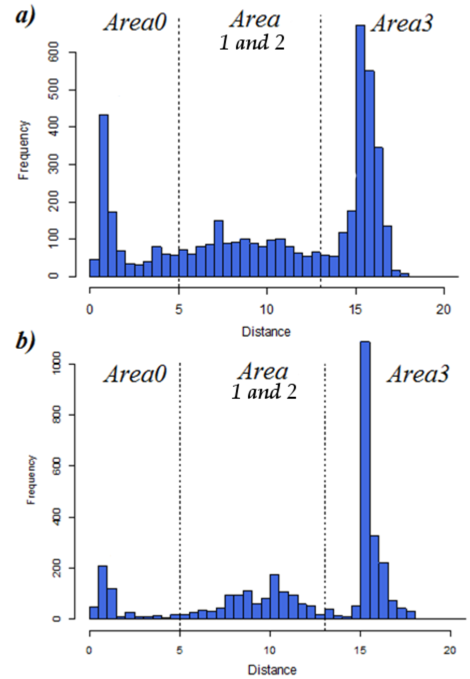

Figure 4. Distance histograms. The distance was calculated from the RSS of the right-left and front-back tilt angles. Distances were calculated for logged operations when drivers a) carefully drove the difficult course (all participants chose course c) in Figure 2) or b) drove at ease (some participants chose course a) whereas others chose course b)).

well as the value of the wheelchair state. The threshold levels, Th1 and Th2, are defined by the distance histograms shown in Figure 4, where the distance is calculated from the root sum square (RSS) value of the right-left and the front-back tilt angles. Figure 4 shows the distance histogram when participants run through the a) most difficult course and b) easiest course. A comparison of Figure 4 (a) and Figure 4 (b) reveal that the number of logged operations is clearly lower in the latter because an easy course requires few stopping or switching (Area 0) operations. The other difference is the number of logged operations in Areas 1 and 2. To quantify the frequency differences in Area 0 and in Areas 1 and 2, the threshold levels were determined by considering the distribution of distances in Figure 4. According to the questionnaires, the distance histogram shows a characteristic distribution in Areas 1 and 2 because of the drivers' conditions. When the driver is careful, the PWC often stops, moves slowly, or turns in the test course. Therefore, the logged operations ranged in low- (Area 0) and middle-level (Areas 1 and 2) operation areas. There are three peaks in the histograms of Figure 4, at around distances of 0, 10, and 15. The number of data points in the distance histogram is too small to approximate the three distributions by Gaussian distributions. Hence, the threshold levels Th1 and Th2 were determined by the midpoints between the peaks in the histogram as 5 and 12.5, respectively. Although PWCs generally have a backlash of the joystick and an offset level of operation, the value of the dead zone is less than 5°. In fact, the PWCs are stopped or slightly moving when the logged operation is in Area 0, i.e., that the wheelchair state is 0. When the wheelchair state is 1, the PWCs adjust their

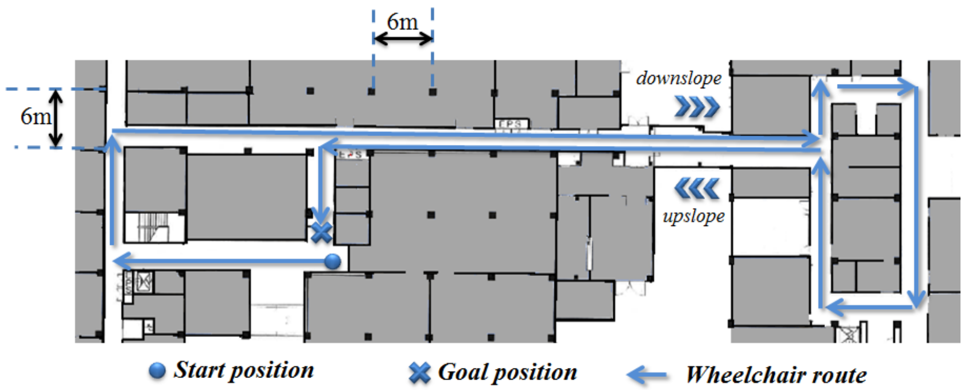

Figure 5. Brief overview of evaluation test course. The modified PWC mounted with the WELL-SphERE system runs through a test course pathway from the start position (marked by a circle) to the goal position (marked by a cross) at a voluntary speed. The total length of the indoor course is approximately 230 m. The test course has a gradual slope of 3.5° relative to the ground.

direction in a careful manner. When the wheelchair state is 2, the PWCs slowly move in the forward direction. Finally, when the wheelchair state is 3, the PWCs rapidly move without carefulness.

The results of the evaluation test are shown in Figure 6. Differences in the depth of color indicate the differences in wheelchair states (≈ driver's degree of carefulness). Figure 6 (a) and Figure 6(b) are the results for participant A, who was an experienced driver, and Figure 6(c) and Figure 6(d) are the results for participant B, who was a novice driver. Figure 6(a) and Figure 6(c) are the estimated wheelchair states and Figure 6(b) and Figure 6(d) are the corresponding actual wheelchair states. The accuracy levels of the estimated states were calculated by comparing the estimated and actual wheelchair states. The results for the mature and novice drivers are 98.8% (a) and 89.0% (c) respectively. However, the difference in the number of logged operations is shown as the difference in the density of the color bars between Figure 6(b) and Figure 6(d). As for Area 0, the accuracy levels of the estimated wheelchair states in Figure 6(a) and Figure 6(c) are 99.8% and 99.3%, respectively. The wheelchair state 0 includes not only the stopped state but also the joystick switching state. Consequently, the accuracy of the estimated wheelchair state is not 100% about Area 0.

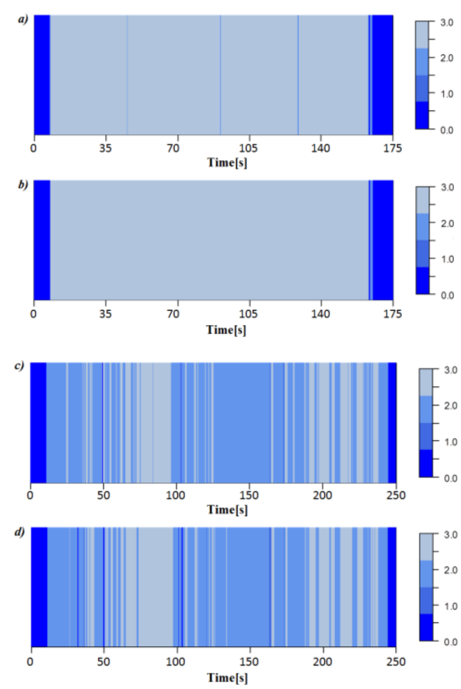

Figure 6. Estimated results of wheelchair state. a) and b) show results for the mature driver who used the PWC over 1 h before this experiment. c) and d) show results for the novice driver who used the PWC once or twice. a) and c) are results estimated from the accelerometers mounted on a joystick. b) and d) are directly recorded joystick voltages corresponding to the joystick angles.

IV. Conclusion

In this study, we focused on the logged operations during the test runs and examined their characteristics. As a result, the logged operations were categorized into four "wheelchair states." The accuracy of the estimated wheelchair states was approximately 90%. Although errors in the estimated wheelchair state occurred when the driver frequently operated the joystick, the sequence of the wheelchair state clearly showed characteristics of driver operations and were not subject to the estimation errors.

A future direction of study will involve combining the wheelchair states with GPS location data to investigate the safety of PWC users.

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