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An optimal sensor placement method for physical function assessment in living space

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Abstract. In recent years, the rapid aging of the population and the high incidence of fall accidents have been problems. Although conventional physical function assessments have been conducted by interviews with physicians or physical fitness tests, research and developments have been recently conducted on a system to be used in medical facilities by using motion capture systems or inertial measurement units to enable detailed and easy assessment. However, contact sensors constrain people's movements during measurements. Furthermore, they may feel nervous during measurement at experimental sites or hospitals, and this causes different movements from usual. Thus, we have been suggesting a physical function assessment system that realizes the measurement of natural daily activities by introducing non-contact sensors into the living space. In conducting physical function evaluation in a living space, it is necessary to consider the set of conditions, such as sensor placement, from the viewpoint of privacy protection. In addition, because of the wide variety of living space designs, the determination of sensor positions is currently tailor-made to take into account measurable motion and privacy, so there is room for optimization. However, to begin with, there are few examples of measurement in actual living spaces, and standards of home-based sensing such as the actual measurable indices, and installation conditions are unclear. Therefore, the purpose of this study was to propose an optimization system for the placement of sensors in the living space for physical function evaluation. We proposed a system that simulates the amount of data on walking motions that can be obtained under each condition and the optimal placement of the RGB-D sensors based on that data. In this study, sensor placement was optimized based on the following three evaluation items: (1) residents do not feel discomfort, (2) walking motions can be measured, and (3) the sensor does not interfere with residents' walking. The system was validated using floor plan information published in CASAS Smart Home Data sets, and we discussed its usefulness and issues.

Introduction

In recent years, the world's population has been aging, and it is essential to prepare for the economic and social problems that accompany this aging. The use of sensing technology is thought to be useful for improving the health problems of the elderly, and many studies have been conducted to use sensors to monitor and evaluate the health conditions of the elderly[1] [2]. In this study, we focused on physical function evaluation, which is useful for early detection of the decline of physical function and disease. It is considered that the physical function evaluation can be used for effective physical therapy intervention and improvement of the living environment. Physical function evaluation has conventionally been conducted by a physician's interview and physical fitness tests[3]. However, in recent years, studies have been conducted on systems that provide

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diagnoses in detail and easily by acquiring joint positions and ground reaction forces using sensors. In previous studies, physical function evaluation was conducted by calculating indices such as walking speed and body inclination from gait measurements under experimental conditions using optical and depth sensors[4] [5]. However, contact-type sensors may put a burden on the person during measurement, and when measuring at an experimental site, the person may move differently than usual due to nervousness[6]. Therefore, it is desirable to conduct physical function evaluation naturally from daily life activities by introducing non-contact sensors in the living space.

However, more detailed data acquisition is required to conduct physical function evaluation in a living space than in a monitoring system to detect anomalies such as falls, so more consideration must be given to the setting of conditions such as sensor placements. Whereas monitoring systems using non-contact sensors only need to understand residents' rough movements, such as a silhouette, physical function evaluation requires detailed data about how the residents move their bodies. Kinetic approaches such as using force plates can measure the balance of the center of mass when walking, but considering the cost and the difficulty of installation, it is not practical to introduce such a system into a living space. Therefore, kinematic approaches, such as using RGB cameras, are appropriate for physical function evaluation in living space, and it is reasonable to use RGB-D sensors which are added depth sensors for more accurate joint position estimation. When installing RGB-D sensors in living space, it is necessary to consider not only the ability to measure movement, but also the discomfort caused by cameras to the residents and the difference in the amount of measurable movement according to the floor plan. However, there are still few examples of measurements in actual living spaces to conduct physical function evaluation, and the criteria for sensor installation are still unclear. Thus, this study proposes a system that optimizes the placement of sensors for physical function evaluation based on the floor plan information.

Materials & Methods

Dataset

In this study, we used CASAS (Center for Advanced Studies in Adaptive Systems), which is publicly available on the web page of Washington State University, for the purpose of acquiring floor plans of houses and walking logs of residents to be used as input for the system[7]. This data set contains a variety of data on the residents' lives over a long period of time in the living space where multiple sensors are installed. The floor plan used in this study is shown in Figure 1. The house was equipped with motion, temperature, and door sensors, and one subject lived in the house for approximately two months. In this study, walking trajectories are simulated under two conditions: one in which the bias in the amount of movement between areas is taken into account based on the ON/OFF information of the motion sensor, and the other in which the amount of movement is equalized. The position of the motion sensor used is indicated by the red point in Figure 1.

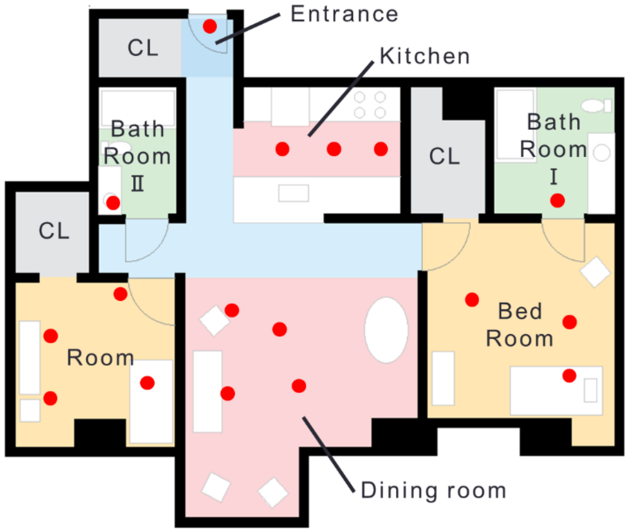


Figure 1. Floor plan

Evaluation items for placement in the system

In the system proposed in this study, the scores of each sensor placement were calculated in consideration of the following three items: (1) residents do not feel discomfort, (2) walking motions can be measured, and (3) the sensor does not interfere with residents' walking. The details of each of these items are described below.

(1) Residents do not feel discomfort

Because RGB-D sensors capture clear images of residents, the residents may feel uncomfortable due to the awareness that their private lives are captured. Thus, we considered that only the flow spaces such as corridors are appropriate for the sensor installation positions, and excluded rooms from the calculation of sensor installation positions in this system to avoid installing sensors into spaces where people stay for a long time.

(2) Walking motions can be measured

In most of the previous studies of physical function evaluation using non-contact sensors, straight walking movements were evaluated. The reason is that straight walking is easy to measure physical function evaluation indices such as body balance during the movement. Therefore, sensor positions where straight walking can be often measured are appropriate. Our system was set to calculate the amount of walking as one of the evaluation values.

(3) The sensor does not interfere with residents' walking

The RGB-D sensors used in many previous studies are put on the floors, for reasons that easy to measure the residents' feet and easy to install and remove. Therefore, our system assumed to use the floor-mounted type sensors. The use of the floor-mounted type sensors is concerned to obstruct residents' walking. Thus, we lower the score according to the amount of walking in the area where the sensor position is overlapped to highly evaluate placing the sensors close to walls or obstacles and are not to be interfered with walking.

Proposed system

To validate the system proposed in this study, a floor plan from the CASAS database was used to calculate the sensor placement considering the evaluation items described in the previous chapter.

The system flow is shown in Figure 2. First, an image of the floor plan was input to read the location of walls and objects. Figure 3 is an image of the floor plan used for input into the system, with other spaces painted gray so that walkable spaces can be read. Also, the image was created with 1 pixel as 1 cm.

Next, the walking trajectory of the resident is simulated. We used the Probabilistic Road Map (PRM) method, a typical method for pathfinding, to predict the walking paths [8]. As shown in Figure 4, by dividing the walkable space in the floor plans by nodes, a path connecting any two points can be calculated while avoiding obstacles and walls. In the validation of this system, we simulated walking between six areas: entrance, kitchen, dining room, bedroom, room, and bathroom I. The calculation was conducted in two ways: one is to move equally 100 times between each area 3000 times in total, and the other is to move 3000 times in total considering the ratio in Table 1 calculated from the ON/OFF information of the motion sensor for about two months. bathroom II was excluded because the motion sensor data indicated that it was seldom used. Starting and ending points were generated at random locations within each area, and each time divided into nodes and searched for a route.

Next, the measurable amount of walking for the sensor position and angle conditions was calculated. As shown in Figure 5, all walking paths were given to each pixel as walking points along with angle information. Then, as shown in Figure 6, only walking points that corresponded to directions within 30° to the left and right of the sensor, and that were not blocked by walls or obstacles, were considered to be measurable straight walking. Also, the size of the sensor stand was set to 20 cm (length) and 20 cm (width), and the measurement range was 60° horizontally and 0.5 m to 3.85 m forward, assuming the Azure Kinect DK (Microsoft, Redmond, WA, USA) which is one of the major RGB-D sensors was installed.[9]。 As described in the previous section, sensor placement was limited to locations where they were in contact with walls and obstacles, and the amount of walking was calculated by changing the angle every 10° at each location on the floor plan. In order to satisfy the evaluation items that the residents do not feel discomfort, the rooms were excluded from the sensor placement candidates, and the door opening/closing range was also excluded.

Finally, the amount of straight walking within the measurable range of the sensor was scored, and points were deducted according to the amount of walking obstructed by the sensor stand. Then, a ranking was calculated from the scores of each sensor arrangement, and the higher ranked ones were displayed on the floor plan.

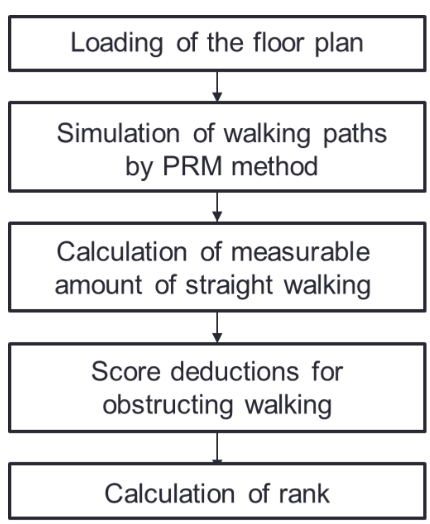


Figure 2. Calculation flow

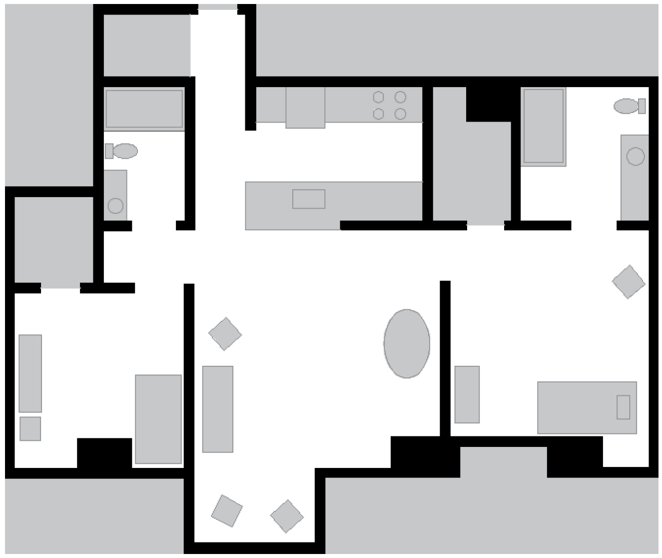


Figure 3. Images of floor plans used as input for the system

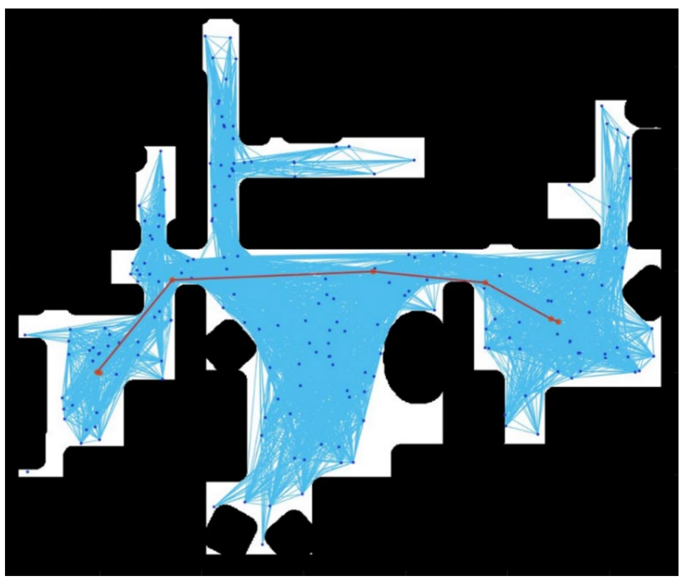


Figure 4. Prediction of walking path by PRM method

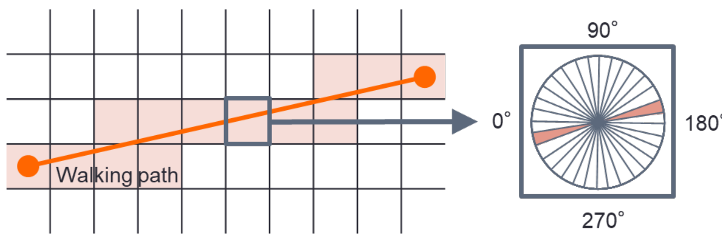


Figure 5. Assigning walking path and angle information to pixels

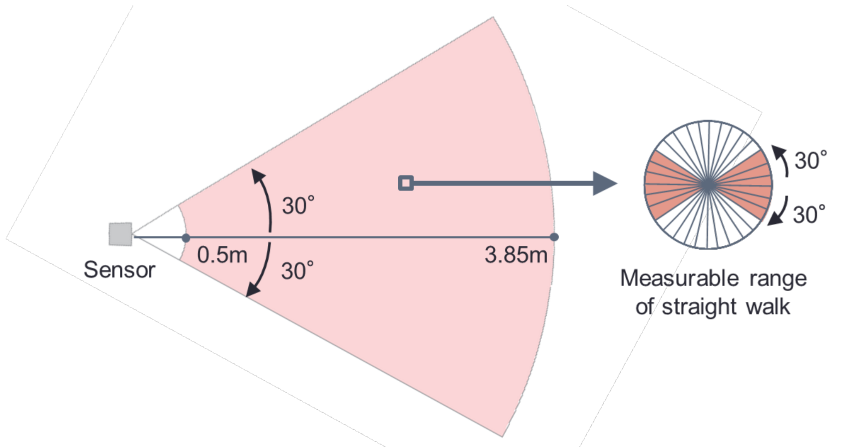


Figure 6. Measurable range of sensor

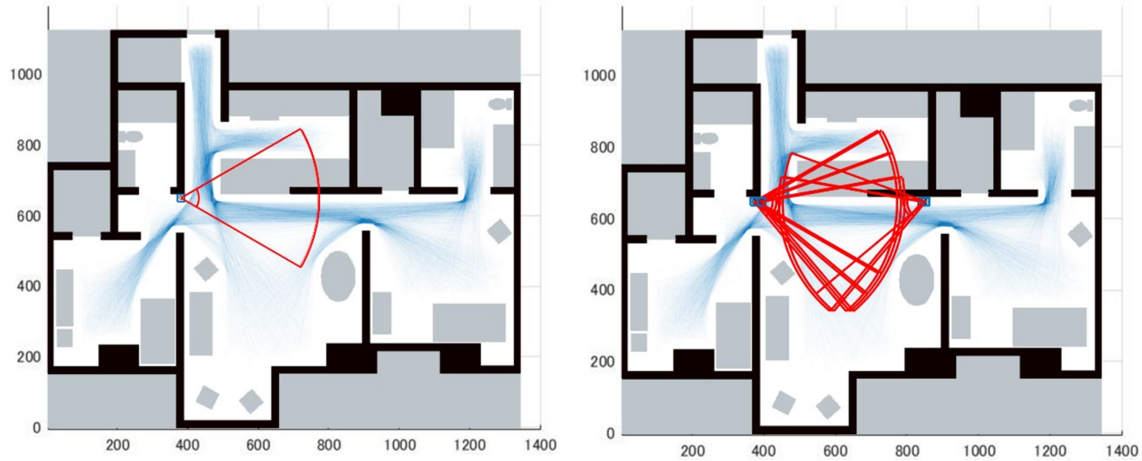
Table 1. Percentage of movement between areas

From \ To	Entrance	Kitchen	Dining	Bed room	Room	Bath room I	Total
Entrance		3%	1%	4%	1%	1%	10%
Kitchen	4%		14%	3%	3%	0%	24%
Dining	1%	16%		5%	3%	0%	24%
Bedroom	4%	2%	6%		0%	11%	23%
Room	1%	2%	4%	0%		0%	8%
Bathroom I	1%	0%	0%	11%	0%		12%
Total	10%	24%	24%	23%	7%	12%	100%

Results & Discussions

Figure 7 (a) and (b) show the simulation results when the number of moves between areas is equalized. The blue lines in the figures show walking trajectories. The best placement was by the wall near bathroom II, where the central corridor walking could be measured. We consider this result to be reasonable because many walking movements can be measured by moving between areas such as the kitchen, dining room, and bedroom, and it is easy to measure straight walking. However, the angle of the sensor causes half of the measurement range to be blocked by the kitchen counter, which is wasteful. This system assumes that measurement accuracy and other conditions are constant within the measurable range of the sensor, but in actuality, there are differences depending on distance and angle to the sensor. Therefore, it is considered necessary to make improvements such as giving a difference in evaluation scores even within the measurable range. Also, the top 10 placements indicate that placement near the bedroom entrance was also rated as a good placement, although the measurement range is almost the same. The placement is not a problem for the measurement range, but it is considered to be an obstacle to walking while opening the bedroom door to the corridor. The system did not take into account the effect of doors opening and closing on the flow line when simulating walking paths, because the simulation was conducted with the doors open. We consider that the walking path can be calculated more accurately by improving the system so that the walking path is also slightly modified by the door opening and closing motion.

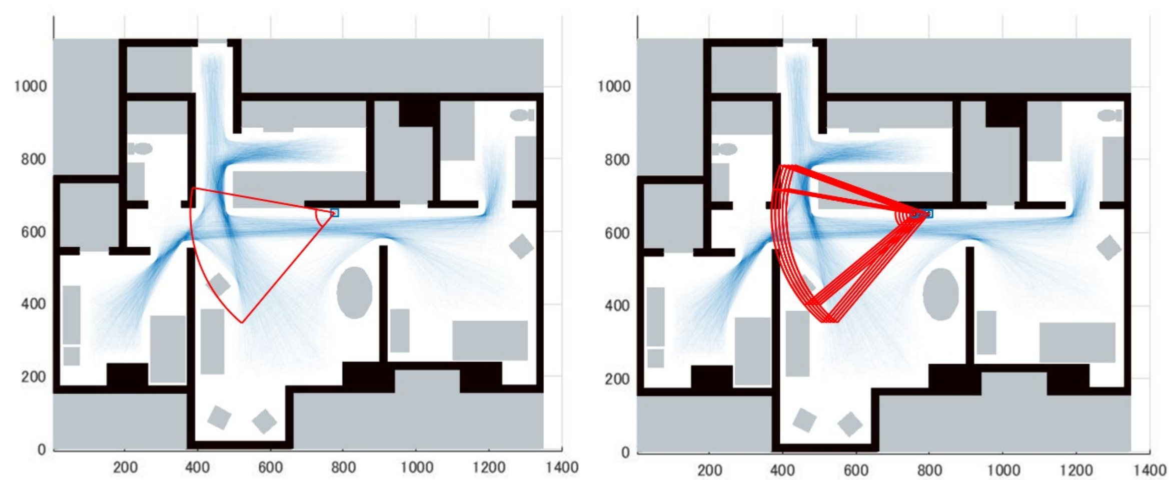
Materials Research Proceedings **27** (2023) 119-126 https://doi.org/10.21741/9781644902455-15



(a) Best Placement (b) Top 10

Figure 7. Sensor placement results for equal number of moves between areas

Next, Figures 8 (a) and (b) show the results when the ratio based on actual life data is taken into account for movement between areas. Both the best and the top 10 sensor placements were captured the central corridor, and the results were similar to the case of equal walking. In the floor plan used in this study, the dining room is open, so placing the sensor on the wall along the kitchen in the central corridor, as shown in these results, is not expected to interfere with walking. Also, the top 10 results were placed in almost the same position, in difference from the equal case. It is thought that this is due to the amount of walking between the kitchen and dining rooms in real life, and that walking was concentrated in the left portion of the central corridor. However, since no significant differences were observed in the walking trajectories, it was found that the consideration of the movement ratio between areas was not very important in this verification. In addition, in the floor plan used in this study, the main bathroom (bathroom I) was attached to the bedroom, but if the bathroom is facing a corridor, it would be necessary to make other considerations such as not capturing the inside. In the future, we would like to conduct further verification using a variety of floor plans and propose a system that can be introduced in daily life.



(a) Best Placement (b) Top 10

Figure 8. Sensor placement results for consideration of movement ratios

Conclusion

In this study, we proposed an optimization system for sensor placement for physical function evaluation in living space that satisfies the following three evaluation items: (1) residents do not

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feel discomfort, (2) walking motions can be measured, and (3) the sensor does not interfere with the residents' walking. In this system, we proposed a sensor placement that can measure straight walking by simulating a walking trajectory using the PRM method based on the floor plan. The results suggest that the prediction of obtainable data in advance can be used to determine the placement of sensors during research and installation. However, since only one floor plan was verified in this study, we would like to conduct additional verification based on the results of this study in order to make the system more suitable for implementation in daily life.

Also, in this study, there was no significant difference between the proposed placement based only on floor plan information and the one that considered the movement ratio based on actual living data. However, in an actual living space, there are many factors to consider, such as the desires of the residents and the number of people in the house. In addition, there is room for consideration of placement not only for measurement of straight walking for physical function evaluation, but also for change of direction and other movements other than walking. In the future, we plan to verify the accuracy by installing sensors in actual living spaces and taking measurements.

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