Entire-Body Capturing System using a Monitoring Robot in a Context of Passing a Pedestrian

Kazuyuki Hayashide[a], Masaki Takahashi[b]

[a]School of Science for Open and Environmental Systems, Graduate School of Science and Technology, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama, 223-8522, Kanagawa, Japan
[b]Department of System Design Engineering, Faculty of Science and Technology, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama, 223-8522, Kanagawa, Japan

1. Introduction

In a society struggling with an aging population or dealing with a pandemic, a shortage of hospital staff will place an increasing burden on medical staff and reduce the quality of life for patients[1]. To address these concerns, automation of transportation and monitoring operations is gaining traction[2]. Robots are replacing transportation services not only in hospitals but also in a wide range of public spaces. Building on this automation trend, it is possible to leverage mobile robots, which are already being introduced in various settings, for patient monitoring tasks as well.

In this paper, monitoring is defined as taking place in a corridor of a hospital ward or a nursing home. There are two reasons for this. First, in hospital corridors with many blind corners, it is difficult for nurses to constantly monitor for wandering or falling patients[3]. Second, physical therapists need to evaluate the gaits of patients in everyday life, not in a rehabilitation room[4][5][6]. For these reasons, the monitoring system is used for gait measurement or monitoring to detect patients who fall or wander around the ward.

This study proposes a mobile robotic system that safely captures full-body images of passing pedestrians, with a view to application for gait measurement or ward monitoring. Also, by exhibiting the motion of the robot and measurement data, the future prospect of the proposed method is discussed.

*Corresponding author
Email addresses: kazuyuki.hayashide@keio.jp (Kazuyuki Hayashide), takahashi@sd.keio.ac.jp (Masaki Takahashi)

2. Overview of the proposed system

2.1. Assumed environment

In this study, a straight corridor with a width of 2.4 m and a length of 15 m is assumed, with no obstacles or other pedestrians, as shown in Fig. 1. The width of the corridor was defined so that the robot could capture a full-body image of a pedestrian passing through, even if the pedestrian walked in the middle of the corridor. Therefore, the proposed system can be used in narrower corridors by using a sensor with a wider angle.

The pedestrian was assumed to be less than 2 m tall and to walk at a speed of 0.3 m/s to 1.2 m/s. In this study, the applicability of the proposed method was also confirmed by experiments with pedestrians who bent at the waist or wore a paralysis experience kit.

The robot that was employed in this study was the TOYOTA HSR-D (height: 1.1 m, radius: 0.3 m, maximum speed: 0.4 m/s) with a ZED-2i stereo camera (angle of view: 110° × 70°, range: 0.2 m to 8.0 m) mounted on its head in a vertical orientation. Motion planning and image processing were performed by a wirelessly connected computational server(Intel Core i7-11700 @2.5GHz).

2.2. Assumed task

There are three requirements for the robot's behavior. First, the robot measures the gait of the pedestrian by walking past each other, expecting that the robot can measure his or her gait from multiple viewpoints. Second, the robot optimizes its motion to capture the full-body images of the pedestrian. This is because observing the entire body of the pedestrian is essential for physical therapists to diagnose the characteristics of his or her gait. Finally, the robot ensures the safety of its movement, a crucial requirement to avoid frightening or colliding with the pedestrian in case of his or her abnormal movements or sudden falls. Therefore, the evaluation of the movement of the robot includes determining when to yield and how to behave when passing each other.

2.3. Structure of the proposed system

The system architecture diagram is shown in Fig. 2. The motion planning part is based on the following formulation proposed in [7] and [8]. The decision variables are a time series of accelerations with respect to the robot's position and neck angle, defined as in (1) and (2).

$$\boldsymbol{u}_R = \left[a_x, a_y, \alpha_{ang}\right]^T \tag{1}$$

$$\boldsymbol{U}_R = \left[\boldsymbol{u}_R\left[k_0\right], \ldots, \boldsymbol{u}_R\left[k_F\right]\right] \tag{2}$$

The time series of the state quantity consisting of the robot's position and velocity is defined as in (3) and (4).

$$\boldsymbol{z}_R = \left[x_R, y_R, \theta_R, \dot{x}_R, \dot{y}_R, \omega_R\right]^T \tag{3}$$

$$\boldsymbol{Z}_R = \left[\boldsymbol{z}_R\left[k_0\right], \ldots, \boldsymbol{z}_R\left[k_F\right]\right] \tag{4}$$

Similarly, the time series of the state quantity of the person is defined as $\boldsymbol{Z}_H$. The optimization problem is defined as follows:

$$\max J\left(Z_R, U_R\right) = \sum_{k=k_0}^{k_F} F_r\left(z_R\left[k\right], z_H\left[k\right]\right) F_\varphi\left(z_R\left[k\right], z_H\left[k\right]\right) \tag{5}$$

$$\text{s.t. } \boldsymbol{z}_R\left[k+1\right] = \boldsymbol{f}_{dynamics}\left(\boldsymbol{z}_R\left[k\right], \boldsymbol{u}_R\left[k\right]\right) \tag{6}$$

$$\boldsymbol{z}_{R\,low} \leq \boldsymbol{z}_R\left[k\right] \leq \boldsymbol{z}_{R\,upp} \tag{7}$$

$$\boldsymbol{u}_{low} \leq \boldsymbol{u}\left[k\right] \leq \boldsymbol{u}_{upp} \tag{8}$$

$$\left\|\boldsymbol{v}_R\left[k\right]\right\| \leq v_{R\,max} \tag{9}$$

$$r\left[k\right] \geq r_{personal} \tag{10}$$

$$\boldsymbol{z}_R\left[k_{0,F}\right] = \boldsymbol{z}_{R0,F} \tag{11}$$

Note that r is the relative distance between the person and the robot and φ is the angle of the person from the robot. The term F_r and F_φ in (5) takes its maximum value when the pedestrian is in the center of the viewing angle. By defining the evaluation function (5) as the sum of $F_r F_\varphi$ over all times, the robot is able to pass each other while keeping the entire body of the pedestrian in the center of the measurable range. Equation (6) represents the dynamics of the robot. Equations (7) and (8) denote the state quantity and control input constraints, respectively. The maximum norm of velocity vector is constrained as defined in (9). Equation (10) outlines the collision avoidance constraint, and (11) constrains the starting position and target positions of the robot.

The robot follows the trajectory planned by the motion planner using the model predictive controller. Even after the robot starts moving, the pedestrian's position and velocity are constantly observed and used for replanning of the trajectory. The update frequency in this research was about 3Hz, depending on the computational speed of the motion planning and image processing. During the execution of the motion, the position and velocity of the person are re-measured and the path is updated at a rate of 3 Hz. This means that the path is updated every 0.4 m for a pedestrian walking at 1.2 m/s. This is thought to be effective in improving the safety of the motion.

3. Experiment

This experiment was conducted to clarify features of the movements of the robot, findings derived from the data obtained, and the issues to be addressed in order to make the system more practical for clinical use.

The experiment was approved by the Bioethics Committee of the Faculty of Science and Technology, Keio University. (Approval No. 2023-030)

3.1. Conditions

The experiment was conducted under the conditions described in Section 2. 36 trials were obtained from 9 healthy subjects (5 males and 4 females, 23.3 ± 0.8 years old, height 1.68 ± 0.11 m, maximum height was 1.88 m), excluding failures such as cases in which the robot lost sight of the pedestrian. The subjects were instructed to walk (i) in a normal posture, (ii) with a bent waist, and (iii) with the paralysis experience kit attached. The subjects were instructed to walk slowly since the main target of this system is a person who has a walking disability. Although this is omitted from this paper, it has been confirmed that the method is applicable to a person walking at a speed of 1.2 m/s in the simulation.

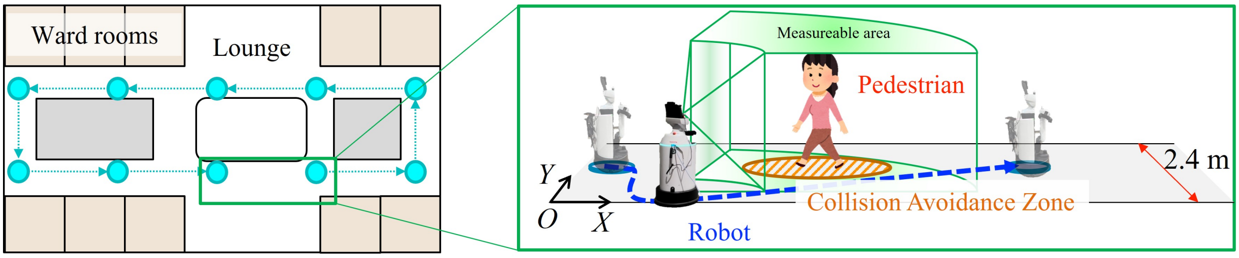

Fig. 1: Assumed environment

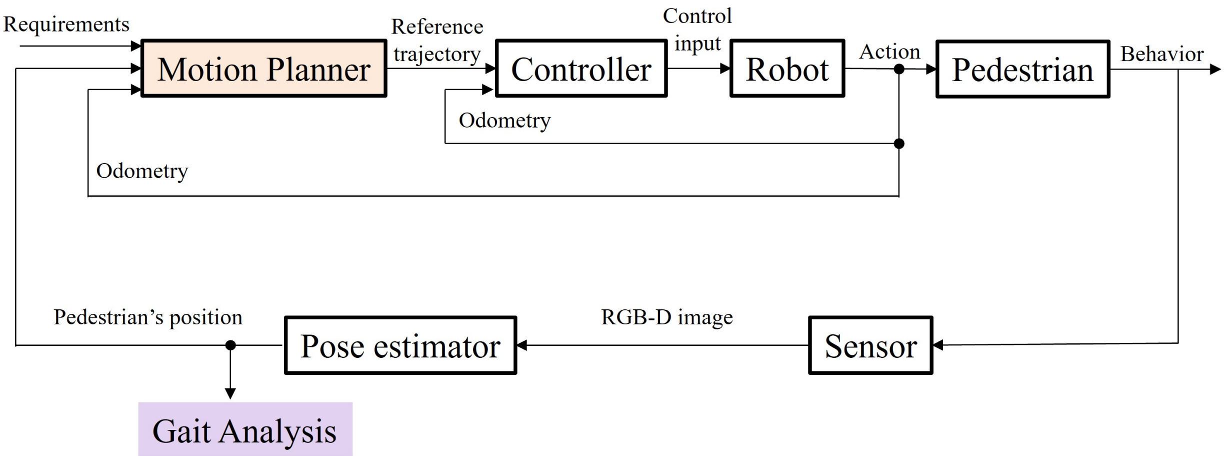

Fig. 2: System architecture

Fig. 3: Motion of the robot and pedestrian

3.2. *Results*

3.2.1. *Motion of the robot*

An example of the situation during the experiment is shown in Fig. 3. The robot first detected the pedestrian coming from the other side and gave way to him. After the pedestrian passed by the robot, the robot resumed its path to the target point.

The motion of the robot exhibited three characteristics. First, the robot made a move to yield the right-of-way early. The robot maintained a distance greater than the collision avoidance constraint in order to capture full-body images of the pedestrian. As a result, the robot was able to give way to pedestrians earlier and they were able to pass smoothly. Second, the robot almost stopped at the edge of the road at the moment passing each other. This was achieved by trying to capture the pedestrian for as long as possible, which is one of the advantages of adding measurement to the robot requirements. Third, the robot stared at pedestrians passing by. This is thought to be due to the sensor's limited angle of view.

The merits and demerits of these three features need

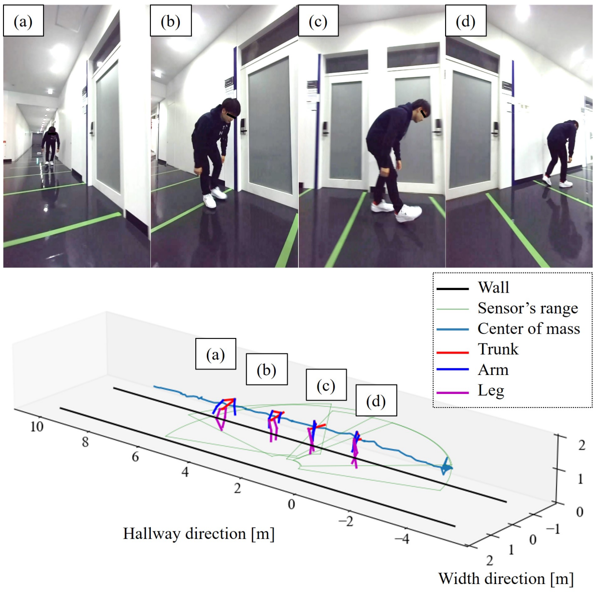

Fig. 4: Data obtained in a trial of scenario (ii)

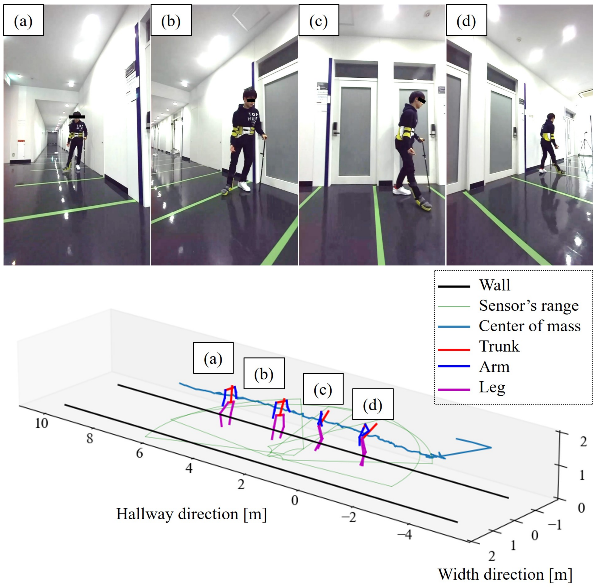

Fig. 5: Data obtained in a trial of scenario (iii)

to be discussed, because it is necessary to investigate what impressions medical personnel and patients have about the movements of the robot. Some people may find it reassuring to know that the robot is acknowledging their presence through its motions, while others may find it uncomfortable because they may feel that they are being watched by the robot.

3.2.2. Obtained data

The robot driven by the proposed method was able to capture the passing pedestrian through an RGB-D sensor on its head. The measurement data exhibited three main characteristics.

First, the robot can record gaits of long distances. As shown in Table 1, it was able to measure the gait of more than 5 m on average. By using time stamps and walking distance, the average walking speed was obtained. In clinical practice, the calculation of walking speed in a similar way is also widely practiced as 5-Meter Walk Test[9], which is one of the most standard methods to diagnose or predict the health status of subjects. Therefore, the proposed system could be used as an automatic testing tool in the future.

Second, as shown in Figs. 4 and 5, the robot was able to capture the entire body of the pedestrian from every angle. It captures front, side and back of the pedestrian in about 30 seconds, so the data contains a variety of information such as hunchback, stability, face direction, limb movement, and so on. Although the effects of noise remain, the pose estimation of Detectron2[10] and center-of-mass trajectories shown in the figures also reflect the characteristics of these gaits.

As for future work, it is necessary to improve the accuracy of pose estimation. In the proposed scenario, it is inevitable that half of the pedestrian's body is occluded, which is one of the causes of reducing the accuracy. Also, the vibration noise of the robot should be one of the main factors for this problem. Therefore, estimation of hidden joint positions and reduction of vibration noise should be addressed.

Once the problem is solved, the proposed system could be useful in that it can automatically collect the gaits of admitted patients. Furthermore, taking advantage of the fact that the sensor itself moves, it may be able to diagnose the athletic or cognitive abilities of the subject by having the robot perform some action on him or her.

4. Conclusion

This paper proposes a novel robotic system that captures images of a pedestrian passing each other in a corridor with a view to applying it to gait measurement and monitoring. The robot ensures the safety of its motion by yielding earlier and stopping when it detects the pedestrian, and resuming its path after the pedestrian passes. The system appears promising as a tool for gait measurement in daily life, as it can capture the entire body of the pedestrian over long distances from any angle. By improving the accuracy of pose estimation and extending its overall capabilities, the proposed system is

Table 1: Results of the experiment

	Time [s]	Distance [m]	Speed [m/s]
(i) walk normally (n = 17)	32.7 ± 4.2	9.67 ± 2.89	0.30 ± 0.10
(ii) walk with back bent (n = 8)	34.0 ± 2.5	8.84 ± 1.40	0.26 ± 0.04
(iii) walk with paralysis experience kit (n = 6)	32.2 ± 8.3	5.55 ± 2.74	0.17 ± 0.06

expected to increase its practicality for automating some of the monitoring tasks in hospitals or nursing homes.

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