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Motion Control of a Walking Support Robot Based on Gait Analysis

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***Abstract* - In an aging society with increasing elder people and decreasing caregivers, the ability to live an independent life is desired to relieve the burden of both the elderly people and the society. Since mobility via walking is important both for independent life and maintenance of good health, various walking assistance devices have been developed. Human-friendly operability is a key issue in the development of these devices for practical use. In this study, we propose to control a walking support robot by the direction of the user's feet. An application was developed to detect the direction of user's feet using an infrared camera. We investigated the accuracy of the developed measurement system and measured the direction of the feet when subjects using the walking support robot. The experimental results showed that although individual differences existed, the proposed method was capable of control the walking support robot to run straight forward, turn right, or turn left intuitively.**

Index Terms – walking support robot, directional intention, infrared camera, gait analysis.

I. INTRODUCTION

Society aging and shortage of caregivers have become serious problems facing many countries. The ability to live an independent life as long as possible benefits both the elderly and the society. Walking ability is indispensable for living independently. However, it is difficult for elderly people to walk alone after their walking ability declined due to aging and the risk of falling down increase. Therefore, various types of walking assistive robots have been developed to support independent walking.

Cane type and walker type are the two main types of walking assistive robots. The feature of cane type is compact in shape, which makes it easy to be used even in a small room with obstacles [1][2][3]. Since the body is supported by a cane, the stability is low and the requirement for the users to handle them is high. Travel control is performed using a force sensor provided in the handle. The walker type devices [4][5][6][7][8][9] are larger than the cane type ones, but is characterized by higher stability.

This study focuses on the control strategy of the walker type robots. Human-friendly operability is a key issue in the development of human assistive devices. Various control methods have been developed for walker type robots. Hsieh et al. [4] and Ko et al. [5] have developed a walker with a force sensor that guides the user to the destination according to the user's walking speed. Yan et al. [6] and Ye et al. [7] developed a walker with a push-pull force that detects the movement of the user's left and right arms. In addition, Ye [7] proposed driving control using ultrasonic sensors to detect the user's walking state and avoid obstacles for safety.

There are many driving control strategies that measure the user's intention use force sensors or laser range finder (LRF). Yan et al. [6] and Song et al. [8] developed a running control using force / torque sensor to determine the user's direction of travel and LRF to calculate the walking speed by measuring the movement of the user's foot. In addition, Song et al. [8] proposed a driving control with LRF on the back of the walker to avoid obstacles for safety. Lee et al. [9] developed a running control using only the LRF that measures the positional relationship between both feet.

However, the aforementioned control strategies only considered to change the direction of the walker by rotating on a spot, and could not control the rotation of the robot while moving forward. According to Yan et al. [6], when the user uses a walking-aid robot to turn to left or right, usually the user will not move his leg, but spin his direction of body to left or right. On the other hand, according to [10], it is known that the movement of a human's body first appears in the direction of the foot, and then in the direction of the pelvis when a person turns a corner. In other words, it is feasible to control the walker to run a curved route by measuring the direction and position of the foot.

In this paper, we propose a new control method by measuring the direction and position of the foot. By extending the driving control method based on the movement of the foot, it is possible to integrate with the control strategies using other sensors to improve the intelligence and safety of a walking support robot.

II. WALKING SUPPORT ROBOT AND GAIT MEASUREMENT

A. *Walking support robot*

Fig. 1 shows the walking support robot developed by the authors. This robot omnidirectional movement with 4 mecanum wheels. This robot can be controlled at a speed in the range of 0 to 0.6 m/s. The height of the table can be adjusted from 850 to 1250 mm by a switch installed on the handle to adapt to the height of the user and to help transfer from sitting position to standing position. There are 4 load cell sensors and two 3 axis force sensors to measure the interaction between the walking support robot and the user, and 5 ultrasonic sensors to detect obstacles. There are two control methods preinstalled for operating the robot.

1) A controller box attached on the table with a joystick to control the direction and a switch to control the speed.
2) A RS-232 interface to receive control signals from an external controller.

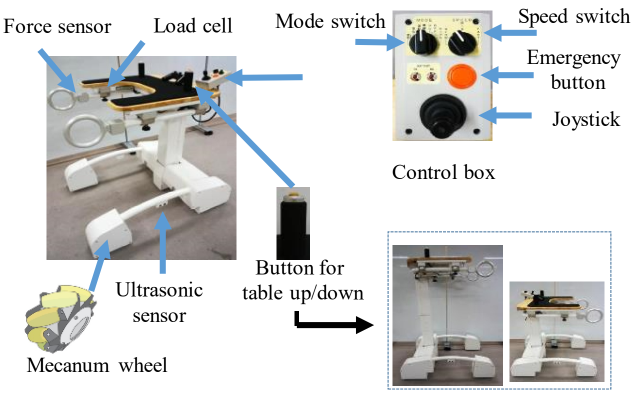


Fig.1: Walking support robot

Operation method 1) controls the direction via a joystick and the speed with 7 different speed levels. Operation method 2) can perform traveling control that guides the user of the walking assistance machine via an interface to receive external control command. In this study, we used method 2) to control the robot and changed the rotations of the four wheels installed in the walking support robot through a application on a computer.

B. *Foot Angle Measurement*

Three-dimensional motion [11] and floor reaction force measurement [12] are typical methods for gait analysis. However, their measurement range is limited because that equipment is large and fixed in the environment. It is preferable that the device used for walking analysis is small and set on the walking support robot to avoid limitation from the environment. RGB-D cameras, which remarkably developed in recent years, have been utilized for human motion analysis [13]. Therefore, we considered a method to analyze walking from the depth image via a RGB-D camera. Fig. 2 shows the RGB-D camera (Kinect V1, Microsoft Corporation, USA) installed on the walking support robot for walking analysis. The measurement frame rate is 30 fps, and the measurement range is 0.4 to 4 m.

We developed an application to measure the direction of the foot using depth images obtained from the RGB-D camera. Fig. 3 shows the processing for the extraction of foot angle from depth images. First, binarization processing is performed for the detection of feet. Fig. 3(a) shows the binarized depth image. Since the walking support robot is supposed to run on plane floors, the foot area has relatively smaller depth. The largest two white areas were extracted as the feet of the user. Then, foot contour was extracted from the feet areas. Finally, the foot direction was calculated based on the contour using principal component analysis. The direction of the first principal component was considered as the foot direction. Fig. 3(b) shows the extracted contours and the calculated foot directions.

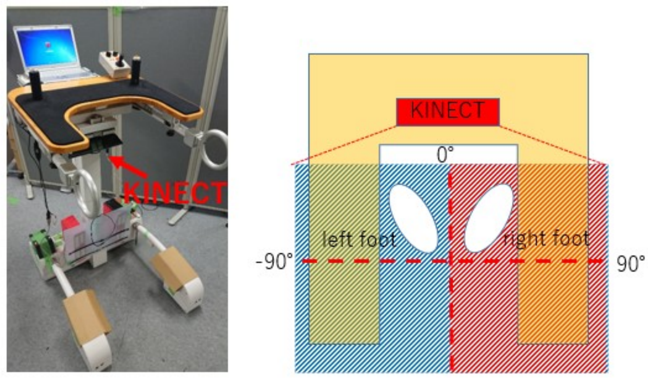
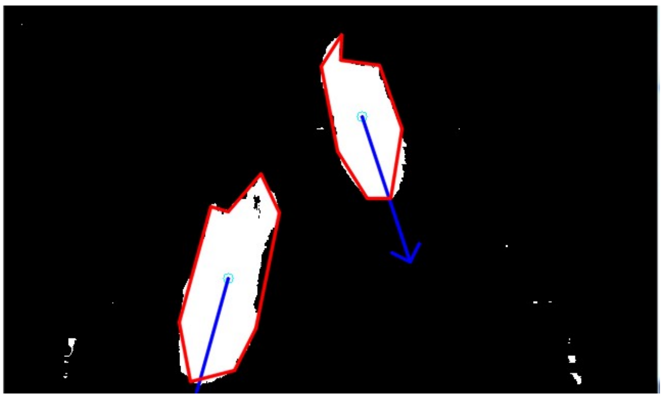


Fig.2 Experimental device and coordinate system setting. The RGB-D camera is installed under the table to measure the foot. Measurement range and coordinate system are shown in the right.

(a) Binarized depth image



b: Contour extraction and foot direction

Fig. 3 Foot direction extraction from depth image

III. Experiments

We conducted two experiments to investigate the accuracy of foot angle extraction from depth image and the feasibility of controlling walking support robot using the direction of the feet.

A. Accuracy of foot angle estimation

This experiment was conducted to examine the accuracy of the developed application that detects the direction of the foot. The angle measurement method was shown Fig. 2. The axis perpendicular to the RGB-D camera was set to 0 degree, with the clockwise direction being the positive direction. The shoes were placed and moved clockwise at 10 degrees intervals and measured from 0 to 90 degrees.

The experimental results were shown in Fig.4. The error between the measured angle and the reference angle was about 2 degrees, which suggest that the accuracy was satisfactory for estimating the foot angle of a user using the robot.

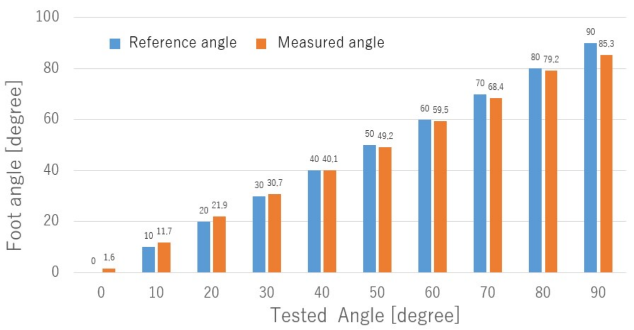


Fig.4: Accuracy of angle estimation. Blue bars show the reference angle, and orange bars show the estimated angle.

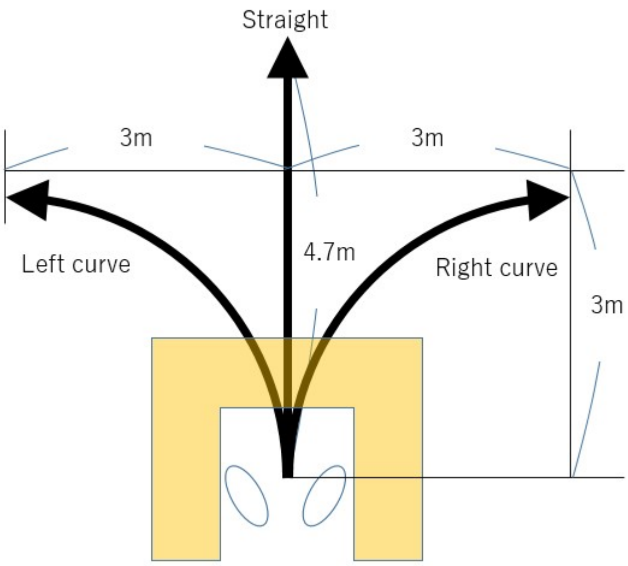
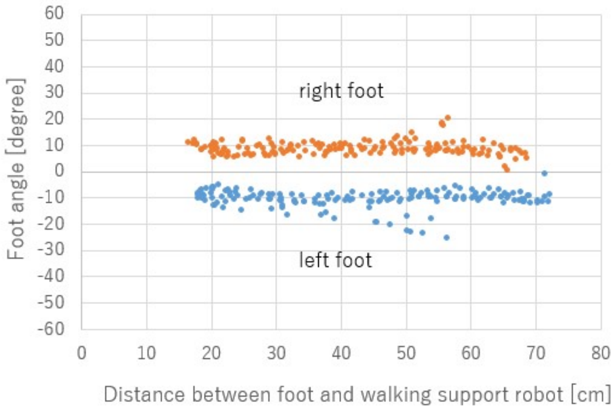


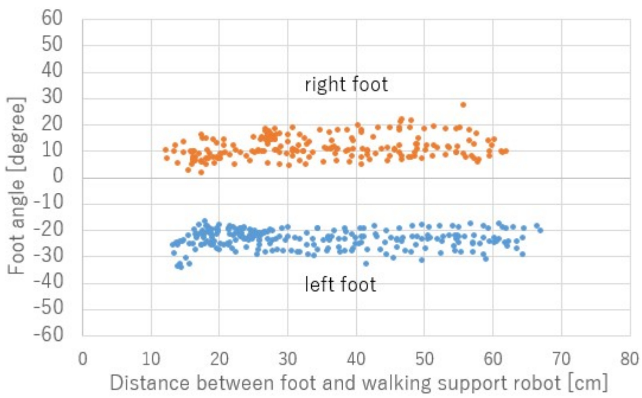
Fig.5 Walking route

B. Foot angle measurement while using the walking support robot

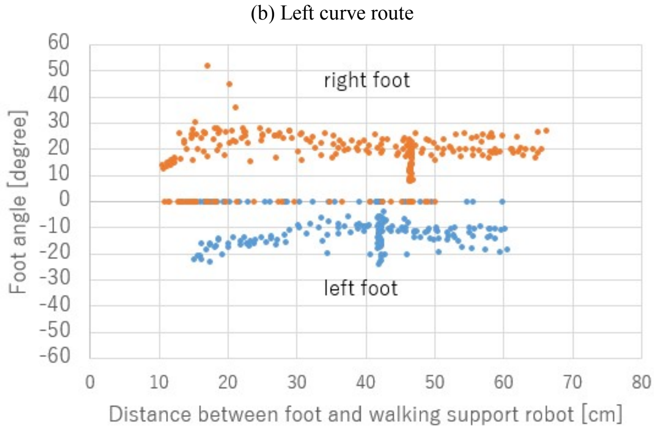
We investigated the direction of the foot when the subject walked following the walking support robot. Three route were studied: straight, right curve and left curve (Fig.5 showed the walking route). The radius of the curved route was about 3 meters and the speed of the walking support robot was 0.53 m / s. The subjects were five adult males, each performed three times for one route. Fig.6 shows the foot angle of one subject with respect to the foot distance from the front frame of the robot (See Fig. 2 for angle measurement method).



(a) Straight route



(b) Left curve route



(c) Right curve route

Fig.6: Foot angle with respect to distance from the robot

The horizontal axis indicates the distance between the walking support robot and the foot. It can be seen that the foot angle while using the walking support robot changes at the range of distance from 0 to 80 cm. Since the foot angle during the swing phase may be susceptible to factors other than walking direction, we focused on the data around the time when the subject's foot was placed on the ground. That is, only the foot angle at the near distance (20 cm or less) was considered in the analysis of walking characteristics of each subject.

The example in Fig. 6 showed that the foot angles of the right and left feet were nearly the same while walking straightly, shifted to the right while waking rightward, and to the left while walking to the left. However, due to individual difference, different characteristics were observed among the 5 subjects. Fig. 7 showed the walking characteristics of the subjects A and B. Subjects A and B both had little difference in feet angle during straight walking. When they walked the left and right curve, the angle of both feet changed greatly depending on the direction of the curve.

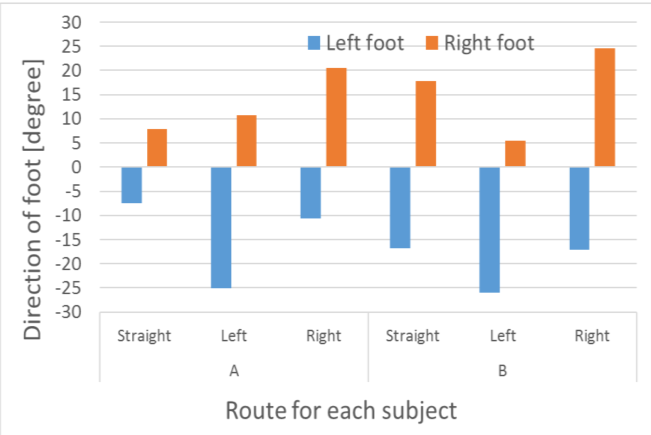


Fig. 7 Direction of foot angle (subjects A and B)

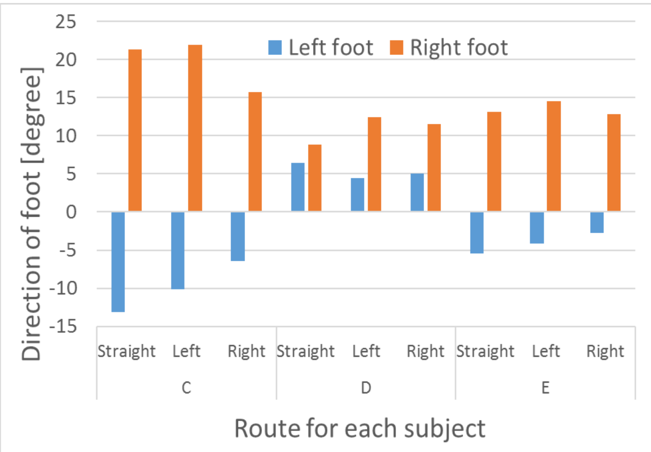


Fig. 8 Direction of foot angle (Subjects C, D and E)

The walking characteristics of the subjects C, D and E were shown Fig. 8. The angles of their right feet were large than those of the left feet during straight walking. For these three subjects, a consistent characteristic could be observed that the right foot angles were larger and the left foot in all the three walking routes.

The results were divided in two groups according to their characteristics. In the experiment, subjects were instructed to walk following the walking support robot. Since the walking support robot was controlled to move the predetermined routes, the subjects did not always move in the direction in which they intended to walk. The reason why subjects A and B had a larger foot angle consistent with the turning direction might be that they wanted to move a smaller radius route than the robot. On the other hand, subjects C, D and E showed no significant difference among the three routes. The constant value between the walking support robot and the direction of the foot showed that subjects C, D and E moved according to the route of the walking support robot, without indicating their own intention.

The abovementioned results suggested that two important things need to be considered to control the walking support robot in the future. One is to examine the walking characteristics of the subject individually. In this experiment, we considered that the walking characteristics of users could be obtained by examining the direction of the feet when running in a straight direction. The other is the relationship between the direction of the foot and the walking support robot when running a curved path. It would be possible to control the robot according to the user's intention indicated by the relationship between the direction of the foot and the direction of the walking support robot. New driving control will be developed using these points.

In this study, we developed the system to measure foot angle using an infrared camera. Next, we will develop a system that measures walking speed. The system configuration is described below. First, the walking speed of the left and right feet is obtained based on the distance data of the infrared camera. This walking speed is converted into the traveling speed of the walking support robot to perform the traveling control. In addition, I incorporate traveling control that prevents the user from being dragged to the walking support machine by measuring the user's walking cycle. The traveling control for turning a curve is performed by utilizing the relationship between the position and foot angle when the user's foot is placed on the ground.

IV. CONCLUSION

In this study, we proposed a running control strategy to control the walking support robot to run a curved path smoothly according to the movement of the user’s foot. We investigated the characteristics of subjects walking with the robot by extracting foot angles from the depth image from a RGB-D camera. Two characteristics were observed: one was that the directions of the left and right feet change according to the direction of walking support robot; the other was that the direction of the foot does not change greatly with respect to the direction. The reason for these results was that whether the user's movement matched the walking support robot.

These results suggested that foot direction is a practical information for the driving control method of a walking support robot. However, individual difference needs to be considered. In future study, we will investigate the relationship between the rotation speed of the walking support robot and the direction of the user's foot, and develop a traveling control method that matches the user's movement.

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