Walking Intent Based Movement Control for JAIST Active Robotic Walker

Geunho Lee, Takanori Ohnuma, Nak Young Chong, and Soon-Geul Lee

***Abstract*—This paper presents a novel interactive control for our assistive robotic walker, the JAIST Active Robotic Walker (JARoW), developed for elderly people in need of assistance. The aim of our research is to recognize characteristics of the user's gait and to generate the movement of JARoW accordingly. Specifically, the proposed control enables JARoW to accurately generate the direction and velocity of its movement in a way that corresponds to the user's variable walking behaviors. The algorithm and implementation of the control are explained in detail, and the effectiveness and usability of JARoW are verified through extensive experiments in everyday environments.**

***Index Terms*—welfare robotics, robotic walker, easy maneuverability, human-robot interaction, walking intent**

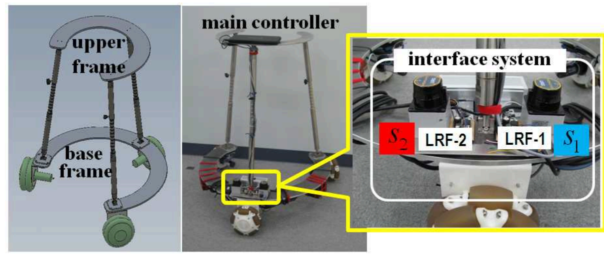

Fig. 1. Prototype of JARoW and its user interface system

I. Introduction

One of the factors essential for everyday life is mobility. Freedom of movement should be available to individuals where they live so that they can lead lives as normally as possible. To determine an individual's mobility status, gait assessment methods typically employed include Performance-Oriented Mobility Assessment (POMA) [1], Functional Ambulation Classification (FAC) [2], and Berg Balance Scale (BBS) [3]. FAC mobility status rates on a 6-point scale from one, indicating a nonfunctional ambulator, to six, denoting an ambulator. The scale describes the degree of human assistance needed to ambulate on flat types of surfaces.

A walker is a device for elderly people who need additional support to maintain balance and stability while walking. Basic traditional walkers mainly consist of a frame surrounded by four legs on the front and sides; body support is provided by the user holding onto the top of the sides. As common structures, four- (or three-) wheel type traditional walkers can be rolled around daily environments with little effort. The merits of these walkers include low cost, simple design, and compact size. However, users must take overly cautious steps so as not to push the walker too far forward, since it lacks a feedback control system. Other disadvantages of traditional walkers include their difficulties navigating carpets, uneven floors with dips and depressions, thresholds, and ascending or descending ramps often encountered in daily routines. Several papers reported that these walkers may increase the risk of falling [4][5]. For example, an unexpected loss of balance might occur if the walkers slips or tips over. Since traditional walkers are considered less safe for use in such conditions, efforts were made to address this issue using additional mechanical devices such as servo brakes [6][7].

Robotic walkers with similar mechanical structures to the traditional walker have emerged, but the installation of costly mechanical and/or electronic components is often required to promote safer ambulatory assistance. Recent technological advances have allowed the incorporation of a range of features into robotic walkers, which can be specialized with physical, sensory, and maneuverability assistances. Moreover, users utilize their own remaining ambulatory capability when walking with such devices, which plays an important role in helping users exercise. The walker therefore needs to be comfortable and easy to use. The robotic walker prototype discussed in this paper, the JAIST Active Robotic Walker (JARoW) [8][9], was developed with these considerations in mind (see Fig. 1). Specifically, JARoW helps elderly people who fit the FAC Category-4[1] profile ambulate more independently, similar to people who fit the FAC Category-5[2] profile. Furthermore, the JARoW's circular shape, light weight, and compact size make the walker easy to use in daily life. Ultimately, JARoW encourages the elderly to lead more active lives, with reduced need for assistance.

Generally, elderly people exhibit slower reflexes and delayed reaction times; moreover, few are familiar with mechanical or electronic controls. Their behavioral symptoms are caused by physical deterioration at both cognitive and sensory levels. Therefore, when designing and developing

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[1](Dependent for supervision): Patient can ambulate on level surfaces without manual contact of another person but, for safety, requires stand-by guarding of no more than one person because of poor judgment, questionable cardiac status, or the need for verbal cuing to complete the task [2].

[2](Independent, Level surfaces only): Patient can ambulate independently on level surfaces, but requires supervision or physical assistance to negotiate any of the following: stairs, inclines, or nonlevel surfaces [2].

robotic walkers for the elderly, an easy-to-learn and simple-to-use interface system capable of responding to complex and diverse environments is of particular importance. Similarly, the interface should be able to accommodate various individual levels of physical capability. Based on an interface that takes into consideration each of the above factors, our goal is to achieve simple, natural interactions during the use of JARoW.

A primary issue is how to provide users with easy yet reliable maneuverability without the use of manual controls. Here, a conceptual term, walking intent, is introduced to facilitate the understanding of our solution. A user's walking intent is defined as an instant walking state representing the geometric relations of the user's lower limb locations observed at each sampling time. It is important to address two basic problems that occurred in the interactions between a user and JARoW: (1) how to recognize the user's walking intent and (2) how to generate motion corresponding to the recognized intent. The JARoW interface, which reads the user's lower limb locations, consists of a pair of laser range finders (LRFs). To effectively detect a user's walking intents, a local coordinate system is defined at the center point of JARoW. Employing this interface, JARoW can autonomously control its motions to correspond to the user's walking intent without any additional user inputs. The objective of this paper is to introduce this walking intent based movement control.

The remainder of the paper is organized as follows: Section II investigates features and interactive control methods for robotic walkers; Section III presents the model definitions, the proposed control, and our implementation goals; Section IV and Section V, respectively, describe JARoW's observation and motion control solutions; Section VI presents experimental results and discussions, and explores possible future directions for development; Section VII contains our conclusions.

II. Background

Recent progress in welfare and rehabilitation robotics has provided a solid foundation for the development of personal robotic mobility aids with the potential to improve the lives of many elderly people. Notable examples include robotic wheelchairs [10]-[12], robotic canes [13][14], and robotic walkers. Among them, the robotic walkers [15]-[21] aim to provide both ambulatory aid and rehabilitation potential. Compared with traditional walkers, the robotic walker is easier to use because it does not require users to use their arms to push or lift it. This is beneficial for users with little arm strength. However, they are still bulky and costly; moreover, due to their complicated operation, they often require considerable skill to use. By integrating a range of useful features into the robotic walkers, they become easier and safer to control. Specialized functionalities for robotic walkers include physical assistance [6][18][21], sensory assistance [9][15][17][20], and maneuverability assistance [16][19]. Depending on the user's physical abilities and needs, ambulatory assistance has been incorporated into these functionalities. A discussion of maneuverability by user-walker interactions is found below.

Input devices for robotic walker interfaces can be classified as direct or indirect, according to the way in which user commands are relayed to the walkers. Direct interfaces include joysticks, touch screens, and voice activation systems. Initially, joysticks [14][22] (or handles [17][20]) integrating force sensing and control were employed to offer more sophisticated maneuverability. When the joystick is moved in a certain direction while walking, velocities (or accelerations) are triggered according to the direction. However, vibrations might occur due to an uneven surface, or the force of the user's foot striking the floor. Subsequently, touch screens [23] were used as a means of simplifying controls; the touch screen is the simplest way to specify a target location intuitionally. Since the input corresponds to the space shown on the screen, visual feedback can be displayed immediately. However, the increased cognitive load involved in using a touch screen rather than a joystick could potentially cause confusion for elderly users, increasing the likelihood of an accident. Third, voice activation systems [24] have many advantages as a bilateral communication interface in transferring effective high-level commands. By translating two speech parameters such as volume and pitch, it is in principle possible to control the motions of robotic walkers. However, critical problems such as interference and voice recognition remain to be solved.

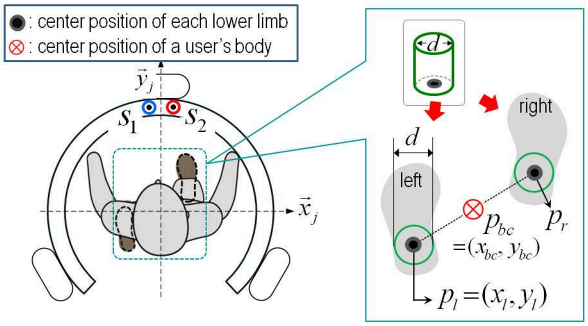
Rather than responding to direct commands, it is desirable that robotic walkers recognize users' intentions indirectly. Examples of indirect input devices include the visual recognition using cameras [12][25], the combination of cameras and proximity sensors [19], human gait detection based on pressure sensors [26][27], and the combination of cameras and pressure sensors [28]. However, an elaborate recognition algorithm and high performance devices must be incorporated into the visual recognition system. Human gait detection also requires the user to wear an additional device, and its use in outdoor environments remains problematic. The use of high-performance interfaces helps ensure accurate measurements in real-time, but might require a complicated and expensive control system. Another innovative idea is a brain-computer interface, which would allow users to control a robotic wheelchair after it reads brain activities [10][11]. However, despite their growing importance, it is premature to talk about universal applications at this stage.

III. Walking Intent Based Movement Control

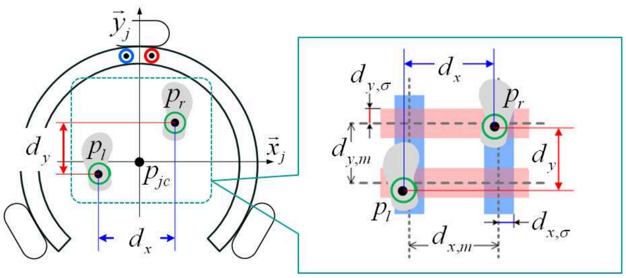
A. JARoW: System Description

Fig. 1 shows a JARoW prototype and its interface system. Compared to other robotic walkers, JARoW's design is compact, and its footprint circular, which reduces the potential for collisions with obstacles or walls. JARoW has three main structural parts: a base frame, an upper frame, and connecting rods. The base frame supports the superstructure, and is directly connected to the drive-train and equipped with two Hokuyo URG-04LX LRFs as the interface system. The length of the connecting rod can be adjusted according to the height of users. Users are able to lean their upper body forward and place their forearms onto the upper frame. Details on the JARoW's mechanical specification and its first-order kinematics can be found in [8][9].

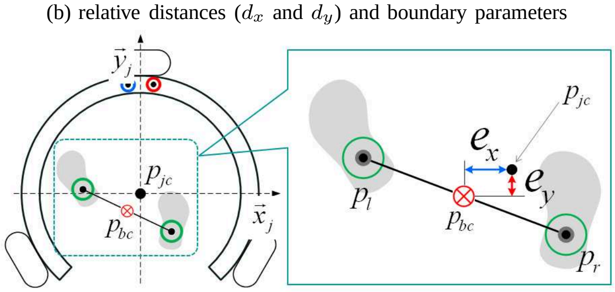
Next, the control components of JARoW consist of the drive-train with three omni-directional wheels, the interface



(a) projected locations of lower limbs: p_l and p_r



(b) relative distances (d_x and d_y) and boundary parameters



(c) position difference between p_{jc} and p_{bc}

Fig. 2. Illustrations of definitions and notations used in the walking intent based movement control

system, and the main controller mounted on top of the upper frame. A laptop PC running Microsoft's Windows 7 is used as the main controller. Details on the controller will be introduced in Section III-D. The interface system is able to detect the locations of the user's lower limbs, as well as obstacles or area borders. In the interface, two LRFs are represented as S_1 and S_2, indicating the left and the right LRF, respectively. Each LRF outputs a 240 degree scan and measures up to 4000mm with 100ms sampling time T (*i.e.*, every sweep interval in the LRFs); pair of LRFs can cover a full 360 degree spectrum. At each T, the interface system outputs the data measured by the synchronized S_1 and S_2, which are fed to the main controller.

B. Model Definitions and Notations

As illustrated in Fig. 2, JARoW's local coordinates are $\vec{x}_j$ (horizontal axis) and $\vec{y}_j$ (vertical axis) where $\vec{y}_j$ is defined as the direction of its forward motion. Its center position is denoted by $p_{jc} = (x_{jc}, y_{jc})$. Measurement data are calculated with respect to the JARoW's local coordinates initialized at the beginning of each T. Accordingly, p_{jc} is (0, 0) with respect to its $\vec{x}_j$ and $\vec{y}_j$ as soon as it updates at each T. Moreover, as mentioned in Section I, the user domain of elderly people for JARoW is based on the FAC Category-4 profile [2], where

TABLE I
NOTATIONS FREQUENTLY USED IN THIS PAPER

notation	description
T	sampling time: 100 ms
$\vec{x}_j$ and $\vec{y}_j$	JARoW's local coordinates
p_{jc}	JARoW's center position: (x_{jc}, y_{jc})
p_l, p_r	left and right centers of individual shins
p_{bc}	body center position of a user: (x_{bc}, y_{bc})
d_x, d_y	dist. differences bet. p_r and p_l in $\vec{x}_j$ and $\vec{y}_j$ directs.
d_{sl}	stride length

the users are able to walk freely with both lower limbs. The lower limbs are modeled as cylinders with a diameter d, representing each shin [8] that is vertically projected onto a two-dimensional plane (for simplicity, $\vec{x}_j\vec{y}_j$ plane, afterwards) with respect to $\vec{x}_j$ and $\vec{y}_j$.

In Fig. 2-(a), the projected centers of individual cylinders correspond to the center positions of a user's shins; the left and right projected centers are defined as $p_l = (x_l, y_l)$ and $p_r = (x_r, y_r)$, respectively. It is assumed that the body of a user extends from the left shin to the right shin on $\vec{x}_j\vec{y}_j$ plane. Employing p_l and p_r, the representative body position $p_{bc} = (x_{bc}, y_{bc})$ is defined as the midpoint on the line segment connecting p_l and p_r. Fig. 2-(b) illustrates the definitions of relative distances d_x and d_y, which denote the differences in distance between p_r and p_l in $\vec{x}_j$ and $\vec{y}_j$ directions, respectively. Moreover, if we consider the forward motion of a user, the right shin shifts from location p_a to location p_b, while the left shin remains fixed. Here, p_r is represented as p_a and p_b according to T. The stride length d_{sl} is defined from p_a to p_b, and t_{sl} denotes the sum of sampling times it took to shift from p_a to p_b. TABLE I summarizes notations frequently used.

A valid region for the location measurement of lower limbs is defined as a rectangle with 900*mm* $\times$ 800*mm* (length and width) on $\vec{x}_j\vec{y}_j$ plane. We assume that p_r and p_l remain within the valid region at each T. Similarly, p_{bc} is assumed to remain inside the same region. In other words, these assumptions indicate that p_l, p_r, and p_{bc} are always observable within the region. Under these assumptions, according to geometric relations between p_l, p_r, and p_{bc}, walking with JARoW can be classified into four walking states: initial/stop, forward/backward movement, step left/right, and turning left/right. Specifically, walking at each T can be determined as a walking state. At T, walking with JARoW can be also represented as instantaneous displacement data (*i.e.*, d_x and d_y), and divided into straight-line and rotational behaviors. A more detailed description of the classification will be provided in Section IV-C. Furthermore, two conditions for the safe use of JARoW pertain. If either p_l or p_r is outside the valid region for $2T$, this condition is called an emergency state. When this state is detected, JARoW makes a sudden stop. As a clothing condition to ensure clear observation by the interface, users are asked to wear long or short pants.

C. Walking Intent Based Movement Control for JARoW

The problem of providing elderly users with easy yet reliable maneuverability is a significant challenge in designing

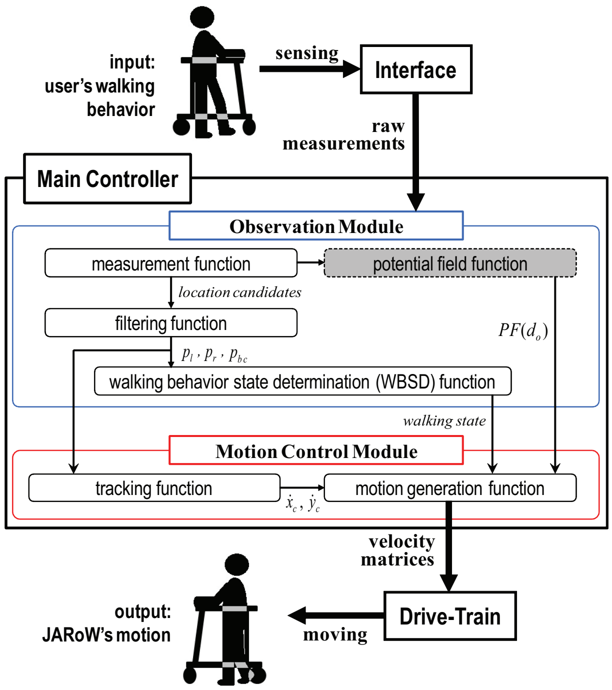


Fig. 3. Data/control flow for the JARoW controller system (Details of the potential field function can be found in [9].)

JARoW's interactive controller. The proposed design provides the solution to this problem. From the viewpoint of interaction, the problem can be separated into two sub-problems: recognition of a user's walking intent and motion generation. Before introducing the proposed solution, we must first formally define the walking intent of a user. Walking intent is a walking state represented using the geometric relations between p_l, p_r, and p_{bc} with respect to $\vec{x}_j$ and $\vec{y}_j$ at each T. Our proposed solution, walking intent based movement control, allows JARoW to recognize walking intents and subsequently generate motions which correspond to the user's recognized intents.

The key aspect of our solution is utilizing the relative locations (*i.e.*, p_l, p_r, and p_{bc}) to generate motion. Using these relative locations, geometric relations are computed to represent the user's walking intents. As the distance measurement is taken at each T, the walking intent is assumed to be linear; the following points are highlighted: (1) JARoW can easily analyze the walking intent without relying on a computationally complex model. (2) Such linear analysis can be implemented with relatively modest resources. (3) The intent estimation is updated at each T, providing tolerance against faulty measurements and motion generation in previous time steps.

D. Main Controller and Implementation

To realize easy yet reliable maneuverability, the proposed solution is embedded in the main controller, shown in Fig. 3. The input to the controller includes measurement data obtained from the interface, and its output is velocity matrices to the drive-train. More specifically, the observation and the motion control modules are designed to play roles in recognizing walking intents and generating JARoW's motions, respectively. Based on measurements derived from the interface, a two-layer Kalman filter is implemented to estimate p_l, p_r, and p_{bc}. By using these outputs, a walking intent can be determined in the walking behavior state determination (WBSD) function. Next, from these observational results, a tracking-based motion generation controller is designed to enable JARoW's motions to accommodate the user's walking intent. A detailed explanation of the functions and the control flows in each module can be found in Sections IV and V.

At each T, JARoW computes a walking intent and its desired motion (computation) based on p_l and p_r (observation), and then drives its motors towards desired termination (motion). JARoW recursively executes the scheduling at each T. When the motion in each scheduling is completed, it is desirable to have JARoW ready to enter a walking state, as this will frequently occur at the next activation. This preparatory state is defined by the controller as the desired termination for JARoW's motion in each scheduling. A detailed description will follow in Section V.

IV. Observation Module

This section describes the observation module, composed of the four functions shown in Fig. 3. This module, with the input data measured in the interface system at each T, outputs both p_r, p_l, and p_{bc} and a current walking state.

A. Measurement Function

The measurement function sequentially performs the two computational processes: data processing and location candidate computation. The first process is to convert the easy-to-handle data in the computation as soon as raw data are transmitted. The inputs from S_1 and S_2 include both relative distances to a surface and the scanning angle corresponding to the distances. To begin, the distance and angle data are converted to Cartesian coordinates with respect to $\vec{x}_j$ and $\vec{y}_j$ in order to allow data separately obtained by S_1 and S_2 to be combined. Simultaneously, the transformed data are sorted into shins and obstacles, respectively, according to the valid region.

In the second process, the location of both shins is computed after the completion of one scan. Each transformed position is checked to determine whether its nearest points are within $40mm$. If the condition is satisfied, it is considered as one surface point on the shins. After collecting the surface points, the continuous data are sorted into left and right clusters where neither cluster exceeds $400mm$. Then, the mean positions of these clusters are calculated. We empirically learned that the mean positions were in the immediate vicinity of the shin's surface, and the distances from the mean positions to the centers of the shins were approximately one-half of its diameter d. Accordingly, these centers can be obtained by adding the mean position to $d/2$. The individual centers are defined as the location of each shin.

B. Filtering Function

The filtering function redefines p_r, p_l, and p_{bc} from measured individual locations after estimation. For this, the standard Kalman filter [29] is employed to accurately detect p_r and p_l in the presence of uncertainties. By recursively matching current locations to predicted locations just before T, it is possible to track them continuously. Moreover, the filtering function allows JARoW to estimate p_{bc} between p_r and p_l, resulting in the ability to read the location of a user's body. To implement the Kalman filter model in the main controller, the state vectors $\mathbf{x}_{i,k}$ and $\mathbf{x}_{i,k}$ representing the positions and velocities of p_r or p_l and p_{bc} are defined as $[x_{i,k}\ y_{i,k}\ \dot{x}_{i,k}\ \dot{y}_{i,k}]^t$ and $[x_{bc,k}\ y_{bc,k}\ \dot{x}_{bc,k}\ \dot{y}_{bc,k}]^t$, respectively, where i denotes the left or right side. Here, it is assumed that p_r, p_l, and p_{bc} move at a constant velocity.

C. WBSD Function

Algorithm 1: Walking Behavior State Determination

Input : $\{p_r = (x_r, y_r), p_l = (x_l, y_l), p_{bc} = (x_{bc}, y_{bc})\}$

$d_x := dist(x_r, x_l)$
$d_y := dist(y_r, y_l)$
if $(d_y < 2 \cdot d_{y,\sigma})$ **then**
  if $(x_{bc} < 0)$ **then**
    STEP LEFT;
  else if $(x_{bc} > 0)$ **then**
    STEP RIGHT;
else if $(d_y \geq 2 \cdot d_{y,\sigma})$ **then**
  if $(d_{x,m} - d_{x,\sigma} < d_x < d_{x,m} + d_{x,\sigma})$ **then**
    if $(y_{bc} > 0)$ **then**
      MOVING FORWARD;
    else if $(y_{bc} < 0)$ **then**
      MOVING BACKWARD;
  else if $((d_{x,m} - d_{x,\sigma} \geq d_x)$ *or* $(d_{x,m} + d_{x,\sigma} \leq d_x))$ **then**
    if $(x_{bc} > 0)$ **then**
      TURNING RIGHT;
    else if $(x_{bc} < 0)$ **then**
      TURNING LEFT;

Output: current walking state

The WBSD function with the input arguments p_r, p_l, and p_{bc} allows JARoW to determine a walking state. Walking is interpreted as either straight-line or rotational behavior simultaneously with the walking state determination. The decision process at each T is presented in ALGORITHM 1. The novel idea behind ALGORITHM 1 is that walking with JARoW is represented by instantaneous displacement data measured at each T. Below is an example of how the instantaneous data are interpreted.

Generally, forward movement is the most dominant state in human walking. When the walking features of individuals are analyzed, forward movement is essential to examine their gait parameters [30]. Among gait parameters, the step width and the step length representing distances between both feet are similar to d_x and d_y, respectively. Here, we recall that d_x and d_y denote relative distance differences in $\vec{x}_j$ and $\vec{y}_j$ directions, respectively. More clearly, p_r and p_l indicate the relative locations of shins with respect to $\vec{x}_j$ and $\vec{y}_j$ at each T. Compared to d_x and d_y, the most obvious difference is based on gait cycle. The human gait is nonlinear, and the gait parameters of individuals are not always steady during walking. Instead, by using the interface under discussion, we are trying to alleviate the need for additional hardware and software to detect exact gait parameters. Hence, the decision process of ALGORITHM 1 is designed based on the instantaneous data at each T.

Due to human anatomical structure and articulation geometry, the sinusoidal displacement of the center of mass for a human body is necessary to achieve forward movement [30][31]. Contrary to this fact, p_r, p_l, and p_{bc} are observed according to T. Therefore, boundary conditions are necessary to determine a walking state. To define the boundary conditions, the three kinds of boundary parameters employed in JARoW are explained. The first boundary parameter is represented by d_x and d_y. The second, as shown in Fig. 2-(b), are the mean distances between p_r and p_l in $\vec{x}_j$ and $\vec{y}_j$ directions, defined as $d_{x,m}$ and $d_{y,m}$, respectively. Unlike d_x and d_y, $d_{x,m}$ and $d_{y,m}$ are obtained by standardizing after collecting d_x and d_y for long intervals with respect to the forward movement state. Based on $d_{x,m}$ and $d_{y,m}$, each pair of the upper and the lower baselines is established along $\vec{y}_j$ and $\vec{x}_j$ where each of the axes divides $d_{x,m}$ and $d_{y,m}$ into two, respectively. Thirdly, the boundaries of distance variations $d_{x,\sigma}$ and $d_{y,\sigma}$ are determined by referring to the standard deviation of $d_{x,m}$ and $d_{y,m}$, respectively. When $d_{x,\sigma}$ and $d_{y,\sigma}$ are applied into individual upper and the lower baselines, the variable boundaries of the individual baselines are confined within $2d_{x,\sigma}$ and $2d_{y,\sigma}$. For example, depending on users, the forward/backward movement states exhibit different d_x variations. For this, the distance boundary of $d_{x,m}$ in $\vec{x}_j$ direction is limited to a distance smaller than $2d_{x,\sigma}$.

ALGORITHM 1 enables JARoW to determine a walking intent by the use of p_r, p_l, and p_{bc}. Under ALGORITHM 1, if d_x is constant within a boundary and d_y is beyond the boundary, and vice versa, walking with JARoW is interpreted as straight-line behavior that includes forward/backward movement and step left/right states. When d_x and d_y are beyond the boundaries, JARoW interprets this as rotational behavior under the turning left/right states. In summary, the observation module outputs p_r, p_l, and p_{bc} and a walking state. Simultaneously, the behavioral interpretation based on the walking intent is obtained. Accordingly, the motion control module allows JARoW to generate its motions to coincide with the interpretation.

V. MOTION CONTROL MODULE

This section describes the motion control module which allows JARoW to generate its motion.

A. Tracking Function

The tracking function based on p_r, p_l, and p_{bc} allows JARoW to compute differences between p_{bc} and p_{jc} , as errors, in $\vec{x}_j$ and $\vec{y}_j$ directions, respectively, and to reflect these errors in JARoW's motions. The basic idea behind this function is that p_{jc} and p_{bc} must remain coincident with each other. The reason why p_{jc} needs to coincide with p_{bc} is twofold. First, JARoW assists the walking of a user so that his or her body is not leaning to either side. Secondly, it effectively avoids bumping into the user while rotating. To accomplish this, a PID$_$BVE controller is designed, integrating a proportional-plus-integral-plus-derivative (PID) controller and a body velocity estimation (BVE) technique.

In Fig. 2-(c), errors between p_{bc} and p_{jc} in $\vec{x}_j$ and $\vec{y}_j$ directions are defined as $e_x = x_{bc} - x_{jc}$ and $e_y = y_{bc} - y_{jc}$, respectively. To minimize errors, the PID controller is realized as

$$\begin{array}{rcl} \dot{x}_c & = & K_{p,x}\ e_x + K_{i,x} \int e_x dt + K_{d,x}\ \dot{e}_x \\ \dot{y}_c & = & K_{p,y}\ e_y + K_{i,y} \int e_y dt + K_{d,y}\ \dot{e}_y \end{array}, \quad (1)$$

where $\dot{x}_c$ and $\dot{y}_c$ are the output velocities of JARoW, and K_p, K_i, and K_d denote the proportional, integral, and derivative gains, respectively.

The user moves in concert with a series of JARoW's autonomous executions, which generate its motions. Despite the use of the PID controller, errors of varying degrees may persist. Accordingly, to minimize the errors quickly and to control discrete or intermittent motions caused by the relative relations, the BVE technique employing an absolute velocity for p_{bc} is proposed so that JARoW can generate its motions more smoothly. Here, we should recall the case of shifting the right shin from p_a to p_b. JARoW calculates the distance from p_a to the current p_r at each T while redefining p_l, p_r, and p_{bc}, and finds the maximum distance which is regarded as d_{sl}. After determining d_{sl}, t_{sl} is obtained.

Given the dominant walking state in human gait, the BVE technique puts restrictions on the forward/backward movement states, namely d_{sl} to both shins only in $\vec{y}_j$ direction. Furthermore, it is assumed that the shins move two times faster than p_{bc} during forward/backward movement. Under this assumption, the absolute body velocity v_{bve} of p_{bc} is obtained

$$v_{bve} \ = \ \frac{d_{sl}}{2t_{sl}}. \quad (2)$$

For the forward/backward movement states, a PID$_$BVE controller incorporating v_{bve} into (1) is given by

$$\dot{y}_c = v_{bve} + K_{p,y}\ e_y + K_{i,y} \int e_y dt + K_{d,y}\ \dot{e}_y. \quad (3)$$

The tracking function computes $\dot{x}_c$ and $\dot{y}_c$ for the PID$_$BVE controller by using e_x and e_y. Note that, from the walking state obtained by the WBSD function, either $\dot{x}_c$, $\dot{y}_c$, or both $\dot{x}_c$ and $\dot{y}_c$ is selected. First, for forward/backward movement states, JARoW is controlled according to (3). Second, only $\dot{x}_c$ in (1) is applied in the step left/right states. Third, during the turning left/right states, JARoW is controlled according to the combination of $\dot{x}_c$ and $\dot{y}_c$ in (1).

B. Motion Generation Function

As shown in Fig. 3, the motion generation function with inputs obtained from three different functions drives the motions of JARoW under the PID$_$BVE controller determined according to walking states, and outputs velocity matrices to the drive-train. The description of the sensory assistance related to obstacle avoidance can be found in [9].

At each T, the motion generation function executed by the outputs of the WBSD and the tracking functions aims to reach the preparatory state given by

$$y_{bc} = y_{jc} \quad (4)$$

and

$$d_{x,m} - d_{x,\sigma} < d_x < d_{x,m} + d_{x,\sigma}. \quad (5)$$

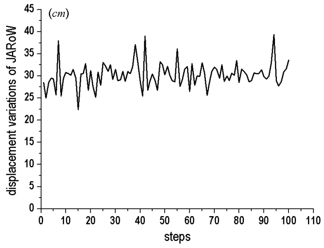
The straight-line and rotational motions are defined in the motion generation function. According to the interpretation of a walking intent, namely the straight-line and the rotational behaviors, one of the individual motions is selected. For the straight-line behavior including forward/backward movement and step left/right states, the preparatory state allows JARoW to move along $\vec{x}_j$ or $\vec{y}_j$ direction. If the straight-line motion of the forward/backward movement states is determined, $\dot{y}_c$ is driven so that y_{jc} coincides with y_{bc}. Similarly, $\dot{x}_c$ is driven for the straight-line motion of the step left/right states. On the other hand, for the rotational motion of the turning left/right states, both $\dot{x}_c$ and $\dot{y}_c$ are triggered where JARoW turns on the axis of p_{bc} until d_x is satisfied within the range of (5). Furthermore, the rotational direction is determined according to the sign of x_{bc} in $\vec{y}_j$ direction. If $x_{bc} > 0$, JARoW turns on the axis of p_{bc} clockwise.

VI. Experiment Results And Discussion

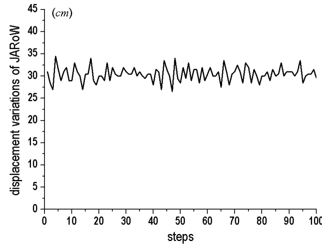
When maneuverability is considered from the two aspects of observation and motion generation, it is desirable that movements triggered by JARoW correspond to the instantaneous displacement data observed from a user's walking. If there is any disparity, JARoW may not be ideally controlled according to the user's walking intent. From a practical standpoint, evaluation criterion and a performance index were designed to examine the extent to which the proposed solution can minimize disharmony between observation and motion. To begin, extensive preliminary experiments were performed with three healthy males in their 20's and 30's to demonstrate the validity and improved performance of the proposed control. JARoW moved under the maximum linear velocity of $1.333 m/s$ throughout all experiments. When it generated a rotational motion, the magnitude of the angular velocity was $0.5 rad/s$. Next, additional experiments were conducted to verify the feasibility and the usability for potential users in their 70's and 80's.

A. Experimental Results

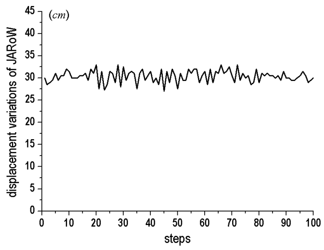
First, to examine JARoW's movement accuracy, the following experiment was conducted. When a subject took 100 forward steps of uniform length of $30 cm$, we checked how accurately JARoW followed the stride length. Figs. 4-(a) and



(a) result of the controller in [8]



(b) result of the PID controller in [9]



(c) result of the PID_BVE controller

	(a)	(b)	(c)
mean	31.86	30.63	30.23
SD	2.76	1.95	1.54
max	39.4	34.5	33.0
min	22.4	26.0	26.5

(d) analytic comparison (cm)

Fig. 4. Comparison of JARoW's displacement variations for uniform stride lengths of $30cm$

(b) show the results performed by our previous controls in [8] and [9], respectively, and Fig. 4-(c) presents the results based on the PID_BVE controller. Compared to Figs. 4-(a) and (b), the contour in Fig. 4-(c) became almost flat. In Fig. 4-(d), the mean value, standard deviation, maximum, and minimum are presented according to individual results. It was confirmed that the proposed control allowed JARoW to generate straight-line motions which closely corresponded to the stride lengths and stride rates of the subject. Moreover, the PID_BVE controller helped JARoW facilitate natural forward movements.

Second, to investigate the validity for the proposed control, circular path tracking experiments were evaluated. A subject walked clockwise along a circular path ('P') with a radius of $1m$. In Fig. 5, the blue dashed line ('$T1$') and the red solid line ('$T2$') show the JARoW's trajectories with the previous control in [8] and the proposed control, respectively. From the trajectories, JARoW could realize smoother rotational motions under the proposed control.

Third, to verify the effectiveness of the proposed control, another experimental setting was prepared where the forward movements of a subject were re-tested by varying the stride lengths in the following order: $15cm$, $10cm$, $25cm$, $30cm$, and $20cm$. Statistical analysis results obtained after 100 trials in succession are presented in Fig. 6, where the error bars represent 95% confidence intervals and the boxes indicate distributions of measured data in the range of 25-75$\%$. Results obtained with the PID_BVE controller showed more accurate displacements compared to the results with the PID controller. This means that JARoW was able to precisely control its motion generation after reading the user's walking intents. Specifically, we observed the widest variations in the $10cm$ stride. However, the strides exceeding $20cm$ showed relatively fewer fluctuations. It was also confirmed that the proposed control is tolerant of faulty measurements and generations in previous time steps.

Fig. 7-(a) shows snapshots for experiments performed under

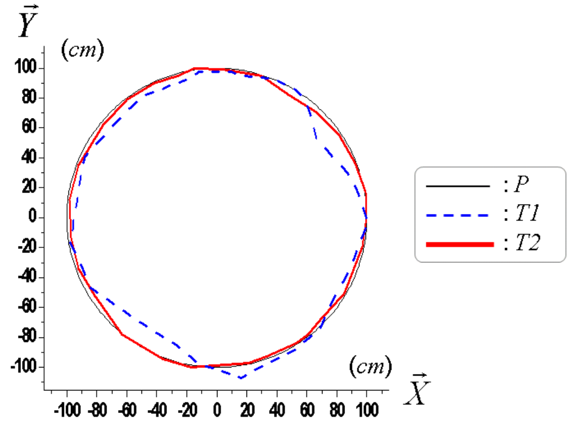


Fig. 5. Trajectories of JARoW following a circular path (thin black line), where the blue dashed line and the red solid line indicate trajectories obtained using the controller in [8] and the proposed controller, respectively

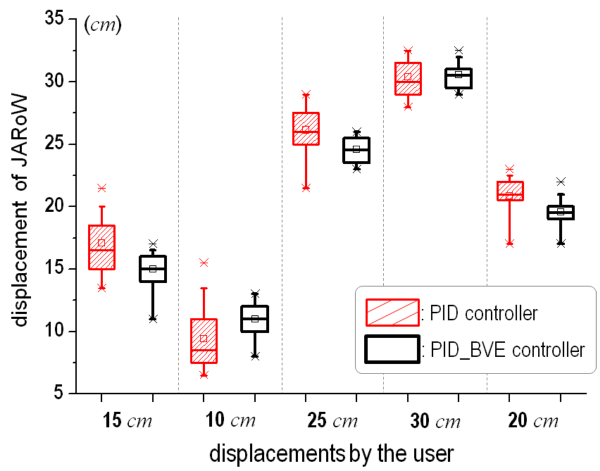


Fig. 6. Comparison of JARoW's displacements based on the PID controller in [9] and the PID_BVE controller, respectively, for different stride lengths

(a) (b)

Fig. 7. Experimental scenes in daily life conditions for (a) performance validation and (b) feasibility and usability testing

the environmental conditions of daily life. These experiments included the straight-line and rotational motions around a corner in a hallway, rotational motions on the spot in an elevator, and forward movement while going up/down in a ramp of 4 degrees, respectively. It was observed that JARoW could be controlled successfully in everyday environments without experiencing any collision. In contrast to existing robotic walkers, our walker features a simpler structure and more compact size and can fit easily into everyday environments.

Next, for the purposes of demonstrating the feasibility and the usability of JARoW under the proposed control conditions and understanding the expectations of its potential users, additional experiments were conducted (Fig. 7-(b)). Before participating in our experiments, written informed consent for the publication of this study and any accompanying images was obtained from the subjects involved in all experiments. Moreover, we briefly explained the use of JARoW and demonstrated its basic performance. Individual subjects were then given five or ten minutes to familiarize themselves with its use.

The experiments were conducted by 5 elderly subjects who use traditional walkers in their daily routines (male: 1, female: 4, age: 75-84 years, height: 149-157cm). A breakdown of the subjects' ages is: 3 persons in their seventies and 2 persons in their eighties. The subjects for the experiments were asked to walk around a hall for about 10 minutes.

After the completion of individual tests, the 5 subjects were asked to fill out the following questionnaire:

- Was it easier for you to walk with JARoW?
- Did you feel safe using JARoW?
- Would you be able to use JARoW in more locations than you use your current walker? If so, why do you think so?
- What kind of functions should be incorporated into JARoW?

For the first question, 3 persons answered yes and 2 persons had no opinion. Here, the 2 respondents said that the ride of JARoW took some getting used to rather than immediate use. Once they got accustomed to walking with JARoW, they responded, "it's easy to use as well." As for the second question, all subject said that they felt safe enough to use JARoW. Next, 4 persons answered yes to the third question. One of the yes respondents said that JARoW seemed to provide safer ambulatory assistance since it could generate its movements corresponding to their displacements and directions. Respondents also expressed dissatisfaction with the unexpected motions of their current walkers on uneven ground. Another person who answered yes was greatly satisfied that JARoW did not require him to use his arms to hold and push it. On the other hand, 1 person expressed dissatisfaction with the bulkier frame of JARoW than her walker. As for the fourth question, respondents said that they would like to see future versions incorporate assistance with standing up/down motions, be more compact and have a lighter frame, and include the ability to ascend/descend stairs.

B. Discussions

Several distinct developments described in this paper can be summarized. The success of walking intent based movement control for JARoW was confirmed through extensive experiments. JARoW demonstrated that it could accurately recognize the users variable walking behaviors and smoothly control the direction and velocity of its movement in a way that corresponded to them. To realize this maneuverability, a key technology was developed which represents linear relations between p_l, p_r, and p_{bc} and allows JARoW to avoid the burden of additional hardware and software to detect exact gait parameters. Since the walking intent is updated at each T, the increased maneuverability also highlights the features of fault-tolerant measurements and generations. Unlike other robotic walkers, this increased maneuverability helps potential users in need of assistance with their daily routines utilize JARoW easily. More importantly, from the mechanical point of view, three omni-directional wheels enable JARoW under the maneuverability autonomously to move forward and backward, slide sideways, and rotate at the same spot. Such omni-directionality provides a very efficient means of direction control in highly cluttered environments, even in a narrow corridor or in an elevator.

Based on the experimental results and the comments of the participants, we could identify future directions for development and refinement, and address issues which need to be resolved. First, JARoW must be able to guarantee safety for potential users; what may occur when using JARoW must be clearly examined from both mechanical and electronic points of view. In addition, nearly 70% of the total manufacturing cost was incurred by the drive-train, which was custom made. To provide better service and comfort for potential users of JARoW, we need to seek technological solutions that will enable cost reduction.

We considered elderly people with a certain level of ambulatory capability as potential users. Although p_{bc} was regarded as the mid-point of the line connecting p_l and p_r, we need to consider the variations of p_{bc} due to the variation in ambulatory levels of potential users. Moreover, to ensure clear observation, respondents are required to wear pants. A more practical version of JARoW will need to incorporate an enhanced interactive control scheme that includes an interface which can accommodate potential users with unusual gaits and does not require users to wear clothing of a particular type.

VII. Conclusions

This paper presented a walking intent based movement control for JARoW without manual user controls or additional control equipment. To accomplish this, we first refined geometric relations between the locations of shins and a virtual planar position modeled as the body center with respect to JARoW's local coordinates. Second, to recognize the walking intents of users, the filtering and the WBSD functions were realized by employing refined models. Third, a tracking-based motion generation function allowed JARoW to generate motions that correspond to users' recognized intents. Fourth, the use of a PID_BVE controller was devised. This effectively controlled discrete or intermittent motions caused by relative relations, allowing it to initiate smooth motions. To demonstrate the validity and effectiveness of the proposed control, elderly subjects currently using traditional walkers participated in extensive experiments to verify the feasibility and usability of JARoW. The results of these experiments were analyzed and compared to our previous findings. From these results, we can confirm that the proposed control could provide JARoW's potential users with easy, reliable maneuverability which does not require any additional equipment or manual controls.

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