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Emerald Article: Motion control of walking assistant robot based on comfort

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Motion control of walking assistant robot based on comfort

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Abstract
Purpose – A walking assistant robot can help elderly people walk around independently, which could improve the life quality of the elderly and benefit our aging society. Ensuring the elderly person's walking comfort with such a robot is very important. At present, the majority of walking assistant robot research does not focus on this field. The purpose of this paper is to examine the requirements of comfortable walking and outline the design of a motion control algorithm for a walking assistant robot, Walkmate III, based on comfort.
Design/methodology/approach – During walking, the walking assistant robot should be able to capture the intent of user, guide the user and move at the same pace as the user. Usually, force or haptic interface is used to detect the user's walking intention. The motion control system then transforms the forces applied by the user into the robot's motion. By surveying the elderly people at a nursing home, the authors find that this transformation is important to the walking comfortableness and should be carefully designed. In this paper, the model of walking assisting process with such kind of walking assistant robot is derived at first. Based on this model, a new motion control algorithm is then designed.
Findings – The elderly hoped that, in all topographic conditions, only small forces were needed to drive the walker during walking. Also, good maneuverability was also very important for a walker, to offer the user comfort, which meant the walking assistant robot should be able to respond to the input forces quickly and precisely. Currently widely-used motion control algorithms cannot satisfy all those requirements. In this paper, a new motion control algorithm is proposed, which can get a fast and precise response to the input forces and the input forces needed to drive the robot are kept at a preferred small level, so that the user will not feel tired during walking. Furthermore, by modifying, force feedback can be realized to improve the comfortableness of walking.
Practical implications – The availability of walking assistant robot with improved walking comfortableness might encourage a wider adoption of robotics in our daily life. It could also benefit our aging society by improving the life quality of the elderly and reducing the pressure deriving from nursing labor shortages.
Originality/value – This paper is of value to engineers and researchers developing walking assistant robots for the elderly people.

Keywords Robots, Control technology, Elderly people, Walking aids, Programming and algorithm theory, Walking assistant robot, Comfortable walk, Motion control

Paper type Research paper

Introduction

The world is aging at a rapid rate. The proportion of older persons aged over 60 has been rising steadily, from 8 percent in 1950 to 11 percent in 2009, and is expected to reach 22 percent in 2050. In China, 14.49 percent of its population is aged over 60 in 2009. At the same time, our society also faces a significant shortage of nursing labor, which leads to a great demand for devices that will extend independence and increase the quality of elderly's life. One of the most common concerns of the elderly people is that they would have trouble in locomotion because of declining physical strength or other health problems. But for the elderly, the ability of walking is essential for a high quality life. Lack of mobility will affect the elderly's life independence and lead to inactivity, which is also not healthy for them. To help those elderly people, various types of walking-aids have been designed.

The conventional walkers can provide walking stability and weight support to the user. Some of them are adjustable in height so that it can ensure the user a good posture during walking. But it is just a passive device. The user needs to apply force/torque to push the walker move around like using a wheeled cart. Later, robotic technology is introduced to extend the walkers' function. A lot of intelligent walkers are designed by researchers from all over the world to service the elderly, such as PAM-AID (Lacey *et al.*, 1998, 2000), the walking support system developed by Nemoto *et al.* (1998) from Hitachi Ltd, PAMM from Massachusetts Institute of Technology (Dubowsky *et al.*, 2000), Pearl (Pollack *et al.*, 2002) of University of Michigan, XR4000 (Morris *et al.*, 2003) of Carnegie Mellon University, the Walking Helper and the RT Walker (Hirata *et al.*, 2003, 2005, 2009), Walker developed by University of Virginia (Wasson *et al.*, 2003), WAR proposed by Inha University (Shim *et al.*, 2005, 2006, 2007), iWalker from University of Toronto (Kulyukin *et al.*, 2008) and JAIST Robotic Walker (Lee *et al.*, 2010, 2011)

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Industrial Robot: An International Journal
39/6 (2012) 564–579

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from Japan Advanced Institute of Science and Technology. With powered traction, those smart walkers are much easier for the frail elderly to use. Besides, they can also sense the user's intention through different kind of human-machine interfaces and intelligently assist the user in walking. PAM-AID (Lacey *et al.*, 1998) utilizes a joystick to capture the user's intention of walking. The position of the joystick indicates the desired walking direction. In the second prototype (Lacey *et al.*, 2000), two user-input options are developed to replace the joystick. The first is instrumented handles that detected small movements in the handles. They could detect if they are being pushed or pulled, or are at rest. The second interface is composed of simple switches, one each for forward, backward, left and right. PAMM of MIT (Dubowsky *et al.*, 2000) equips a six-axis force-torque sensor mounted under the user's handle to capture the user's intent. The speed and direction of PAMM is determined from the forces and torques the user applies to the handle. The Walking Helper (Hirata *et al.*, 2003; Chuy *et al.*, 2004) also utilizes a six-axis force-torque sensor to detect the user's intent, which is installed between the support frame and the mobile base. XR4000 of Carnegie Mellon University (Morris *et al.*, 2003) equips a haptic interface which consists of four force sensors to capture the intention of the user, as shown in Figure 1(a). Force-sensing resistors are installed inside two handlebars and pressure readings from sensors are directly transformed into planar translational and rotational velocities. A forward push on both the handle bars results in a forward motion, while a differential push-pull combination results in a rotary motion, which is in accord with the user's preconceived notion. The walking support system of Hitachi Ltd (Nemoto *et al.*, 1998), WAR of Inha University (Shim *et al.*, 2005, 2006, 2007), Walkmate I and II (Shi *et al.*, 2010; Zhang *et al.*, 2011) also adapt this method: two force sensors are utilized to detect the applied pushing/pulling forces. Walker developed by University of Virginia (Wasson *et al.*, 2003) uses two six-DOF force/moment sensors and a digital motion capture system to infer the relations between applied forces/moments and the intent of the user. Based on the user's intent, the robot guides the user intelligently. For the smart walkers mentioned before, force or moment is conditioned and inputted to the controller as operational command. By some smart walkers, the user does not even need to push or pull the robot any more. With the help of sensors, those smart walkers can capture the user's intensions actively. For example, JAIST Robotic Walker (Lee *et al.*, 2011) uses two laser sensors to detecting the user's lower limb locations, from which the user's body position is calculated. Based on those data, typical behavior patterns of moving forward/backward and turning right/left are modeled and used to detect the user's walking intention (Figure 2).

Besides assisting walk, those smart walking-aids can also monitor the user's health, remind the user about their daily activities, provide current orientation and location of the user, detect and remind the user of obstacles and offer navigation service. But at present, there are few researches focusing on the relation between the motion control of the robot and the user's walking comfortableness. It is also important to ensure that the elderly feel relaxed during a longtime walk. This paper aims to examine the requirements of comfortable walking. Based on those requirements, a motion control algorithm is designed and implemented in our walking assistant robot Walkmate III.

This paper is organized as follows. After the introduction, our experiment platform Walkmate III will be introduced at first. Then the walking assisting process with Walkmate III will be modeled and analyzed. To find out the requirements of comfortable walking, a comfort survey was carried out among the elderly people at a nursing home and its result will be listed. Based on the survey result, the walking comfortableness using some existing motion control algorithms will be evaluated. Then a new motion control algorithm aiming at giving the user a more comfortable experience will be proposed. Evaluation experiments were conducted among the elderly people to examine the acceptability of the new algorithm. Finally, conclusions will be drawn and future work will be given in the last section of this paper.

The Walkmate III

The Walkmate III, as shown in Figure 3(a), is the third conceptual prototype of our walking assistant robots. Compared with the Walkmate I (Figure 1(c)) and the Walkmate II, mechanical structure and control system of Walkmate III has been improved and simplified for the elderly people. It integrated the advantages of Walkmate I and II (Zhang *et al.*, 2011). The main body is composed of aluminum sections, which are strong enough while weight low. A pair of casters is adopted as front wheels and two rear

Figure 1 Intelligent walking-aids from all over the world

(a) (b) (c) (d)

Notes: (a) XR4,000; (b) iWalker; (c) Walkmate I; (d) Walkmate III

Industrial Robot: An International Journal
Volume 39 · Number 6 · 2012 · 564–579

Figure 2 The haptic interface of walking assistant robot, which is used to capture the user's intention

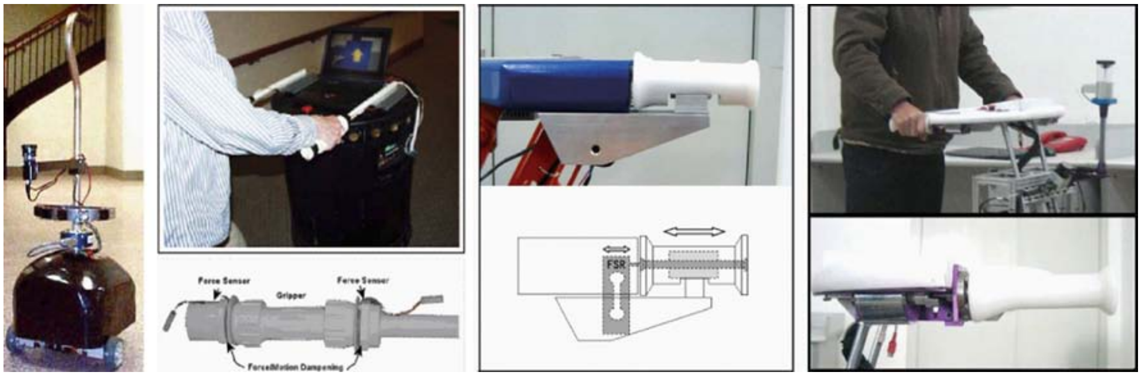
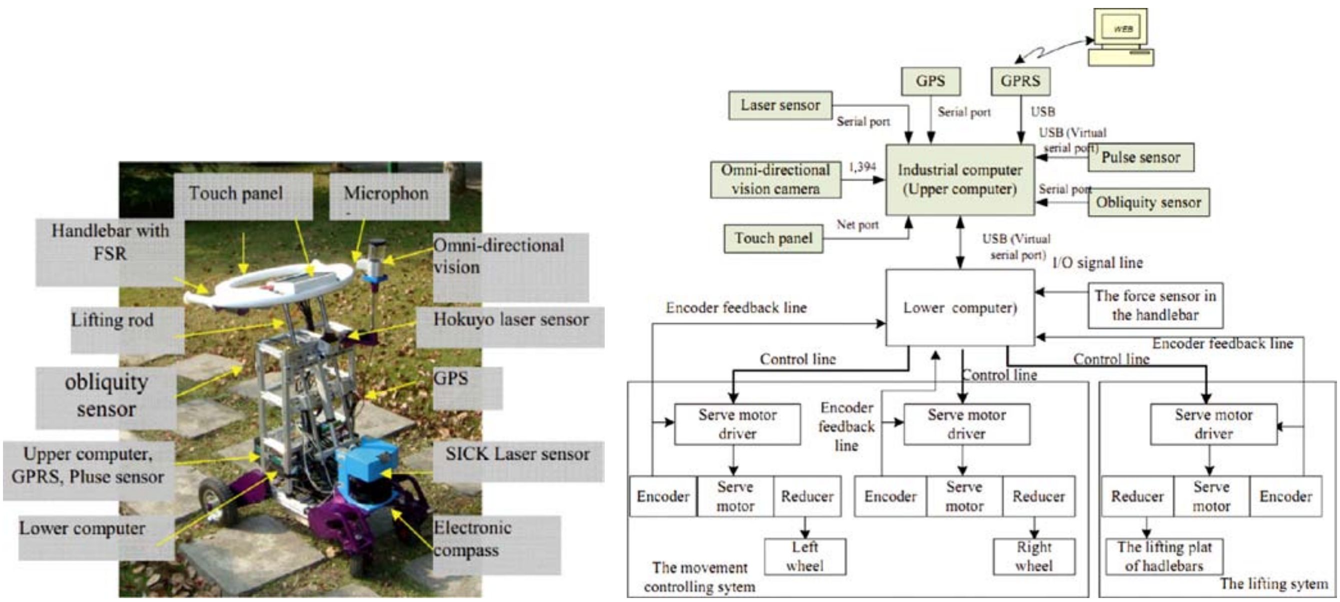


Figure 3 (a) The Walkmate III and (b) the control frame of the Walkmate III



(a) (b)

wheels are driven by two DC motors. Two force sensors are installed in the handlebars of the walker to detect the user's intention. And the user can also control the robot via voice. In addition, a Sick laser sensor is employed for the obstacles detection and SLAM. A Leadtek GPS module is utilized for location and an omni-directional vision is for user tracking. Besides, the user's health information can be monitored and sent back to user's doctor or family through the web server by a CPC V818 GPRS module. The central controller of the Walkmate III is an industrial computer and its OS is Windows XP SP2. The block diagram of the control system is shown in Figure 3(b).

The walking assisting process

Our walking assistant robot Walkmate III utilizes a haptic interface to capture the user's intention. The haptic interface consists of two force sensors installed in two handlebars, which can also provide body support to the elderly. Input forces are measured and transformed into the robot's motion. Force applied on each handlebar determines the speed of the servo motor installed on each side. The user can push or pull both handlebars to drive the robot forward or backward, push left and pull right handlebar to turn right, or push right and pull left handlebar to turn left. In this way, the human-robot interaction system can offer the elderly a nature and intuitive way to manipulate the walking assistant robot, which is consistent with the user's preconceived notion of how a walker should operate.

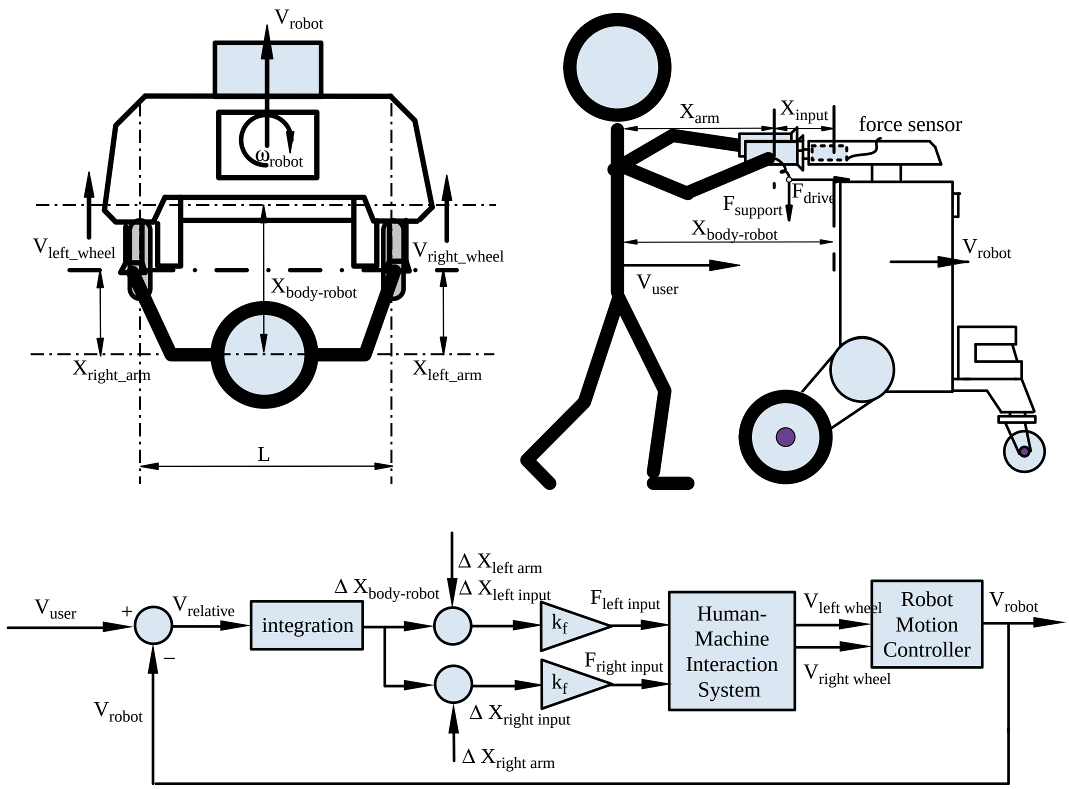
The walking assisting process with such a haptic interaction system is shown in Figure 4. The robot is driven by two differential wheels, so we have:

$$\begin{bmatrix} V_{robot} \\ \omega_{robot} \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{L} & -\frac{1}{L} \end{bmatrix} * \begin{bmatrix} V_{left\ wheel} \\ V_{right\ wheel} \end{bmatrix} \quad (1)$$

in which, L is the distance between two wheels. During walking, the user walks at a speed of V_{user}, while the robot moves with a speed of V_{robot} (and an angular velocity of ω_{robot} if the user wishes to change direction). So, the relative velocity between the user and the robot is:

Industrial Robot: An International Journal
Volume 39 · Number 6 · 2012 · 564–579

Figure 4 Theoretical model of the walking assisting process



$$V_{relative} = V_{user} - V_{robot}$$

Normally, the relative velocity $V_{relative}$ should be zero so that the robot moves at the same pace with the user. When $V_{relative}$ is nonzero, the distance between the user's body and the robot changes and the variation $\Delta X_{body\text{-}robot}$ is the integral of $V_{relative}$. Also taking the length of the user's arm into account, the deformation of each force sensor ΔX_{input} is:

$$\begin{aligned}\Delta X_{input} &= \Delta X_{body-robot} - \Delta X_{arm} \\ &= \int_{D}^{t} (V_{user} - V_{robot})\, dt - \int_{D}^{t} V_{arm}\, dt\end{aligned}$$

The force applied on the sensor can be linearly treated as $F = k_f * \Delta X_{input}$ in the near area of the equilibrium position (where $\Delta X_{input} = 0$). The applied force is then measured by the control system as input. Two servo motors of the robot are driven according to the input forces based on different motion control algorithms. So, we can get the velocities of two wheels:

$$\begin{aligned}\begin{bmatrix} V_{left wheel} \\ V_{right wheel} \end{bmatrix} &= f_{haptic interface}\left(\begin{bmatrix} F_{left input} \\ F_{right input} \end{bmatrix}\right) \\ &= f_{haptic interface}\left(\begin{bmatrix} \int_0^{\tau}(V_{user} - V_{robot})dt - \int_0^{\tau} V_{left arm} dt \\ \int_0^{\tau}(V_{user} - V_{robot})dt - \int_0^{\tau} V_{right arm} dt \end{bmatrix} * k_f\right) \\ &= f_{haptic interface}\left(\begin{bmatrix} V_{user} - V_{robot} - V_{left arm} \\ V_{user} - V_{robot} - V_{right arm} \end{bmatrix} * \frac{1}{S} * k_f\right)\end{aligned} \quad (2)$$

Submitting equation (2) to equation (1), we have:

$$\begin{bmatrix} V_{robot} \\ \omega_{robot} \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{L} & -\frac{1}{L} \end{bmatrix} * f_{haptic interface}\left(\begin{bmatrix} V_{user} - V_{robot} - V_{left arm} \\ V_{user} - V_{robot} - V_{right arm} \end{bmatrix} * \frac{1}{S} * k_f\right) \quad (3)$$

From equation (3) we can see that, the user can manipulate the robot by changing X_{arm} (outstretch or bend the arm) or changing V_{user} (speed up or slow down) during walking.

User's comfortableness during walking

Currently, there is no widely accepted definition of the user's comfortableness in the walking assisting process. Based on the comfort's theory, comfort is a cognitive comparison between actual objects and some point of reference, meaning that expectation and earlier experience affects the user's evaluation of comfort. Thus, the feeling and degree of comfort is dependent on the surroundings, the situation and the individual. To assess the user's comfortableness during walking, the general idea is to ask individuals about comfort factors in the interviews.

To evaluate the comfortableness of walking assisting process, elderly people at a nursing home in Shanghai Minhang District who had the experience of using a walker were consulted. First, several questions arise about the comfortableness of walking were posed, such as "do you feel comfort when walking with your walker, if not, why?" and "what functions do you think are most important for a walker to offer you a comfortable walking?"

Industrial Robot: An International Journal
Volume 39 · Number 6 · 2012 · 564–579

From the elderly people's answers, we summarized all facts that might affect the comfortableness of walking. Then we asked the elderly to vote on whether those facts important are or not for a comfortable walker. Of the 97 eligible elderly people who were asked to participate, 92 (94.8 percent) provided consent. The participants' ages ranged from 61 to 79 with a mean age of 67.8 years old (standard deviation = 5.2). About 53.3 percent of the participants (49) were females and 46.7 percent (43) were males. And 18.5 percent of those participants (12 males and five females) had suffered from leg problems. Almost all participants had used wheeled walker before, such as the products of Bai Appropriate St. and Alidge. The vast majority of participants reported that good maneuverability was very important for a walker to offer the user a comfortable walking. A walker which was hard to manipulate would make the elderly feel disquiet and terrible. And most participants said that they were fairly comfortable when walking with the walker on the flat terrain but felt tired when climbing up/down a slope or walking across a threshold (they had to apply bigger forces to push the walker across the threshold). They just hoped, they only need small forces to drive the walker forwards in all topographic conditions. Besides, safety was also a key factor to ensure the elderly's comfort. Only a reliable walker could enable them feel relaxed during walk. More than 70 percent of the participants thought it would be comfort if they could sit on the walker when felt tired during walking. And about half of the participants reported that they wished their walkers could play music and receive broadcast programs. Almost all elderly participants agreed that, they would be very happy if the walker could help them walk upstairs or downstairs. In contrast, the elderly put little attention on the walker's weight if the walker was motor powered. Similarly, only 11 percent participants thought it was necessary to install a fan on the walker, which would make them feel comfort in summer. The result of the survey is provided in Table I.

In this paper, we will mainly focus on improving the physical comfort of the user by modifying the robot's motion control algorithm (function $f_{haptic\ interface}$ in equation (3)). According to the result of the survey, improving the maneuverability of the walker and reducing the load of the user during walking will be our target. To offer the user a good maneuverability, the robot should be able to respond to the input forces fast and precisely, which means $V_{relative}$ in Figure 4 should be suppressed to zero as soon as possible. The faster and the more precise, the better (Wickens *et al.*, 2004). To make the user feel relaxed during walking, the input forces needed to drive the robot (F_{input} in Figure 4) should be small in all conditions. For the adults, the operation force should be no bigger than 60 N (Ding *et al.*, 2000; Guo and Yang, 2005). While for the elderly, the operation force needed should be smaller, better no bigger than 20 N.

Motion control algorithms and its comfortableness

At present, there are two control algorithms massively adopted by the walking assistant robots: force-velocity mode and force-acceleration mode (or so-called admittance control mode).

Force-velocity mode

In the force-velocity mode, the velocity of robot's wheel is directly set in proportion to the applied force, which means the robot will run or stop instantly when the user's hands on or leave the handlebars. If the user lessens the force to the robot, then the robot reduces its speed, and when no force is given to the robot, it stops naturally. It can be described as:

$$\begin{bmatrix} V_{left\ wheel} \\ V_{right\ wheel} \end{bmatrix} = f_{haptic\ interface}\left(\begin{bmatrix} F_{left\ input} \\ F_{right\ input} \end{bmatrix} \right) = \begin{bmatrix} F_{left\ input} \\ F_{right\ input} \end{bmatrix} * k_v \tag{4}$$

From equations (3) and (4), we can get the system's differential equation of motion:

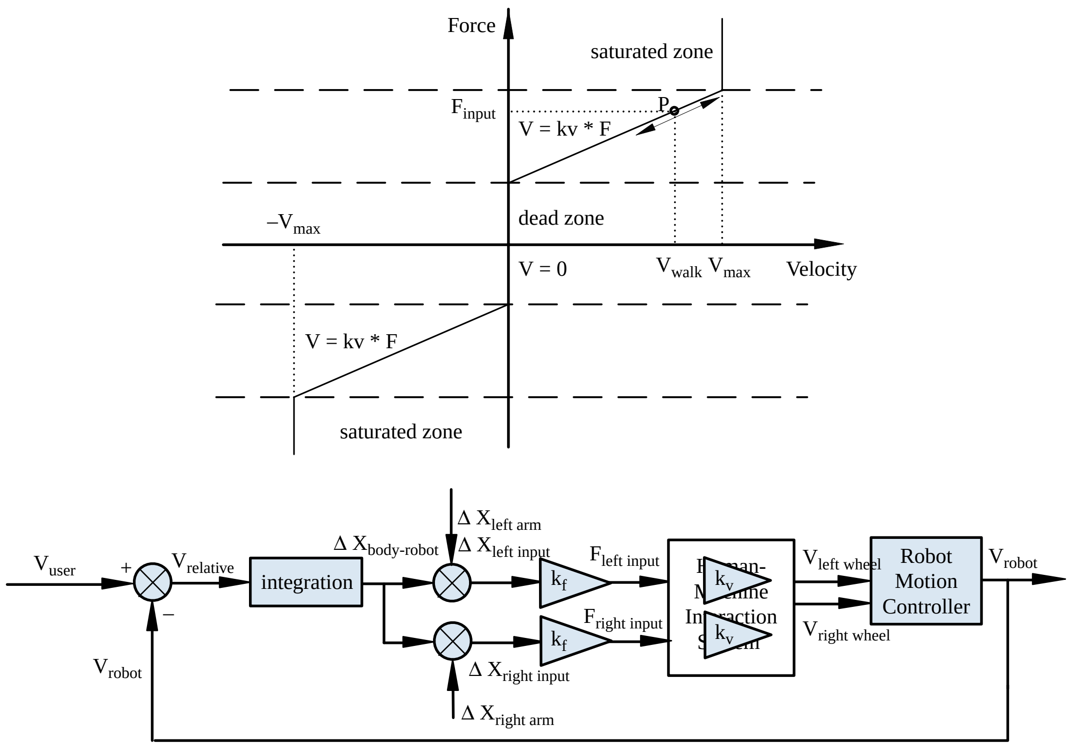
$$\begin{aligned} \begin{bmatrix} V_{robot} \\ \omega_{robot} \end{bmatrix} &= \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{L} & -\frac{1}{L} \end{bmatrix} * \begin{bmatrix} V_{user} - V_{robot} - V_{left\ arm} \\ V_{user} - V_{robot} - V_{right\ arm} \end{bmatrix} * \frac{1}{S} * k_f * k_v \\ \begin{bmatrix} \dot{V}_{robot} \\ \dot{\omega}_{robot} \end{bmatrix} &= \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{L} & -\frac{1}{L} \end{bmatrix} * \begin{bmatrix} V_{user} - V_{robot} - V_{left\ arm} \\ V_{user} - V_{robot} - V_{right\ arm} \end{bmatrix} * k_f * k_v \end{aligned} \tag{5}$$

In practice, a dead zone is added to prevent null shift of the robot caused by disturbances. The block diagram of force-velocity mode and force-velocity curve are shown in Figure 5. Force-velocity mode is intuitive and simple to the elderly and robot can response to the user's intent fast in this mode. Hence it is massively adopted by walking assisting robots as mentioned before, such as the walking support system of Hitachi Ltd, XR4000 of Carnegie Mellon University, Walkmate I and II, etc. But there is also a disadvantage with this mode: when the elderly walks with a speed of $V_{user} = V_{walk}$, input forces needed to drive the robot ($F_{(left/right)\ input}$) equal to V_{walk}/k_v, as the point P shown in Figure 5. The faster the walking speed V_{walk} is, the bigger the input forces are. And during walking, the forces should always be maintained on the handlebars so that the

Table I The result of the survey: are those facts important to make you feel comfort when using a walker?

Category	Factors	Not important (%)	No opinion (%)	Important (%)
Physical comfort	Good maneuverability and convenient operation	0	4.3	95.7
Physical comfort	Small forces needed to drive the walker	2.2	26.1	71.7
Physical comfort	Lighter weight	29.3	59.8	10.9
Physical comfort	Safety and reliability	0	1.1	98.9
Psychological comfort	Radio/music playing function	13	35.9	51.1
Psychological comfort	Cooling fan	38	51	11
Psychological comfort	Can provide user a seat	14.1	12	73.9
Psychological comfort	Can help user walk upstairs/downstairs	1.1	7.6	91.3

Figure 5 Walking assisting process in the force-velocity mode



robot could keep the same speed with the user ($V_{robot} = F_{input}*k_v = (V_{walk}/k_v)*k_v = V_{walk}$), which is really a hard job for the elderly and will make the user feel tired. With the help of Matlab, a simulation of a walking process in the force-velocity mode is carried out, as shown in Figure 6, from which we can also see that, big input forces are needed during the walking. Bigger k_v can be used to solve this problem, but with a bigger k_v, the walker will move too fast even when the applied forces are small, which will damage the maneuverability and make the elderly feel unsafe, as described later in the evaluation walking experiments.

Force-acceleration mode

To overcome the disadvantages of the force-velocity mode, force-acceleration mode (or so-called admittance control algorithm (Chuy *et al.*, 2004; Shi *et al.*, 2010)) is introduced and implemented in the walking assisting system. As the name suggests, the acceleration of robot is set proportional to the force applied in the force-acceleration mode. The motion control system amplifies the applied force signals and outputs the acceleration of each wheel. Each wheel is then driven to move with the calculated accelerations. By this means, the motion control system simulates the motion of a real cart and can make the user feel as if they are using a conventional walker. The block diagram of force-acceleration mode is shown in Figure 7. The acceleration of each wheel is:

$$\begin{bmatrix} a_{left\ wheel} \\ a_{right\ wheel} \end{bmatrix} = \begin{bmatrix} F_{left\ input} \\ F_{right\ input} \end{bmatrix} / k_a \qquad (6)$$

in which, k_a can be treated as the virtual equivalent mass of the robot. And from equation (1), we can also get:

$$\begin{bmatrix} \dot{V}_{robot} \\ \dot{\omega}_{robot} \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{L} & -\frac{1}{L} \end{bmatrix} * \begin{bmatrix} \dot{V}_{left\ wheel} \\ \dot{V}_{right\ wheel} \end{bmatrix} \qquad (7)$$

Submitting equation (7) into equation (6), we can get:

$$\begin{bmatrix} \dot{V}_{robot} \\ \dot{\omega}_{robot} \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{L} & -\frac{1}{L} \end{bmatrix} * \begin{bmatrix} F_{left\,input} \\ F_{right\,input} \end{bmatrix} / k_a$$

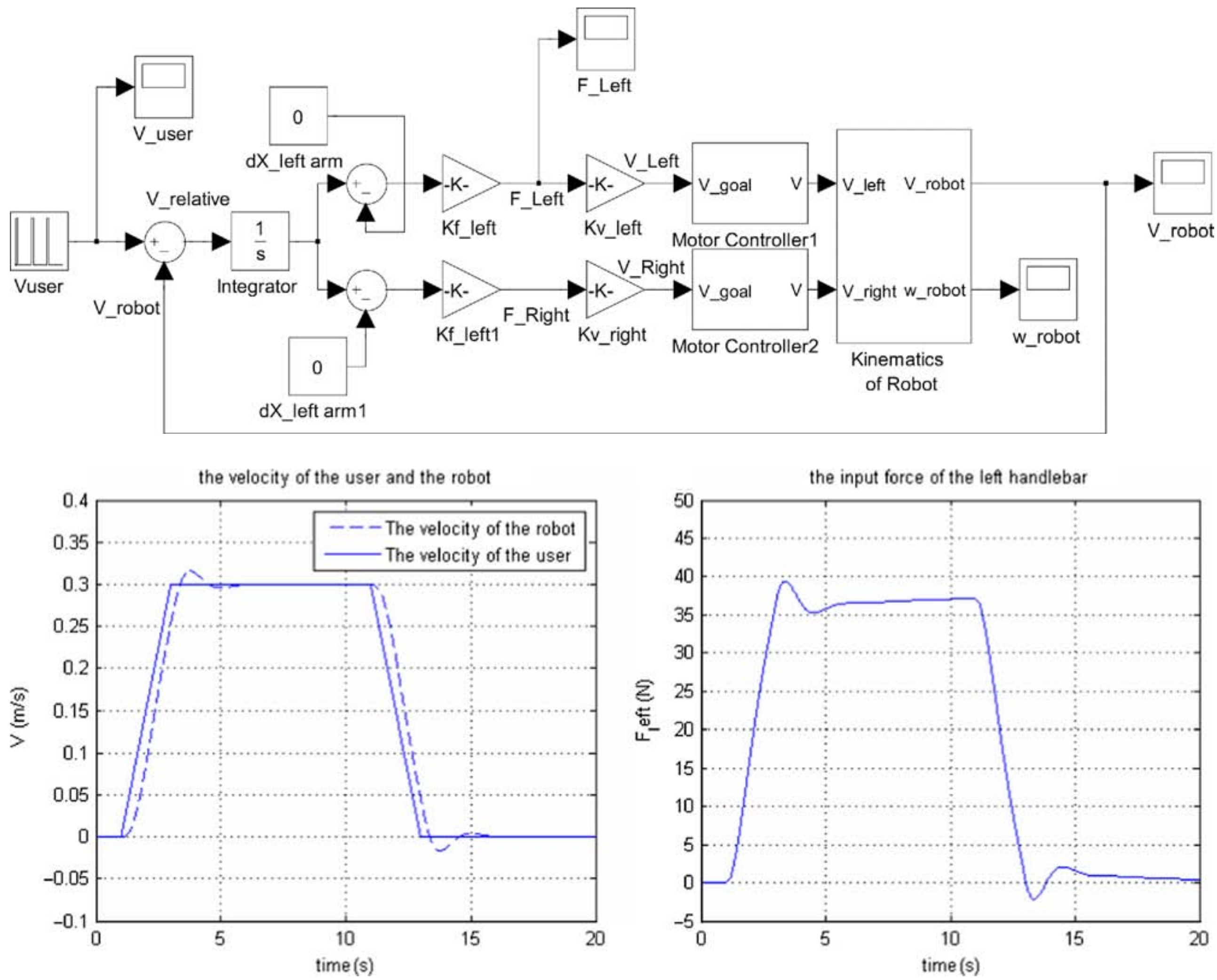
$$= \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{L} & -\frac{1}{L} \end{bmatrix} * \begin{bmatrix} V_{user} - V_{robot} - V_{left\,arm} \\ V_{user} - V_{robot} - V_{right\,arm} \end{bmatrix} * \frac{1}{S} * k_f / k_a \qquad (8)$$

From equation (8) we can see that, this control algorithm can make the user feel as if they are controlling a conventional walker (with a virtual equivalent mass of k_a). In practice, a virtual damping D_a is added so that the robot will gradually slow down just like a real cart when user's hands leave the handlebars, which is also a measure to ensure the safety. Thus, at each moment, the actual acceleration is:

$$\begin{bmatrix} a^{actual}_{left\ wheel} \\ a^{actual}_{right\ wheel} \end{bmatrix} = \frac{\begin{bmatrix} F_{left\ input} \\ F_{right\ input} \end{bmatrix} - \begin{bmatrix} V_{left\ wheel} \\ V_{right\ wheel} \end{bmatrix} * D_a}{k_a} \qquad (9)$$

So in this mode, the user only needs to accelerate the robot to the desired speed V_{user}, and then applies a small force on the handler to maintain this speed during walking. In this way, the user would not feel tired during walking. But in practice, there are also some disadvantages with this mode. First, due to an integral element in the control system, the robot's response to the input

Figure 6 The simulation result of a walking process in the force-velocity mode with the help of Matlab



Notes: Kf = 180; Kv = 0.008

force is delayed. To get a fast response, a bigger force is required, which is not what the elderly expect. Second, it is a little hard for the user to control the speed of the robot accurately. That is because in the force-acceleration mode, the control algorithm simulates an inertial system. It is really difficult for the user to control an inertial system accurately manually. Overshoot is common when controlling such a system, as shown in Figure 8. The user needs to adjust input forces over and over (by outstretching or bending the arm) to get V_{robot} close to the desired velocity V_{user}, which harms the comfort of walking.

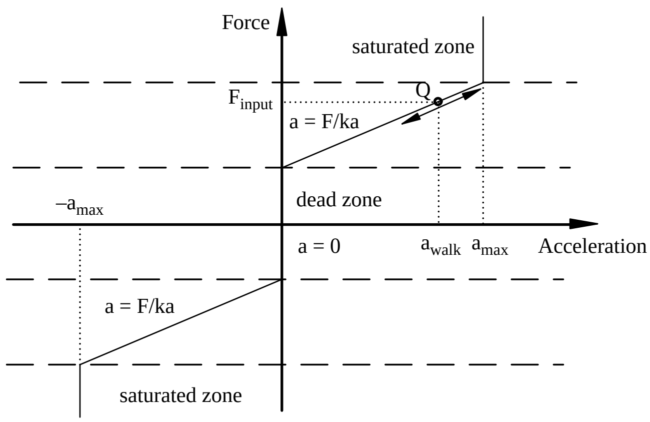
Comfortable walking mode

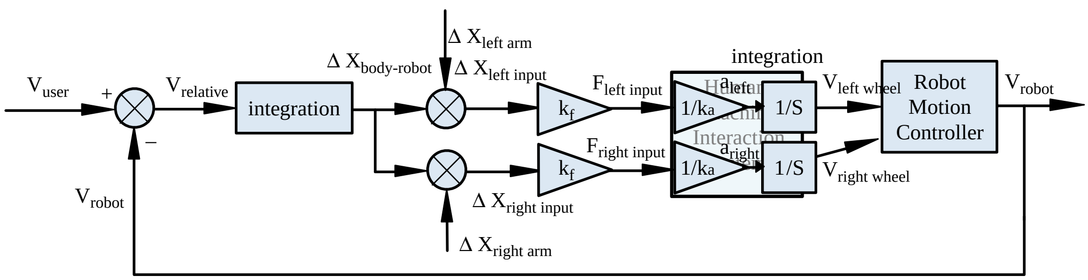
As mentioned before, walking assistant robot in the force-velocity mode can response to the input forces quickly, but the user needs to keep exerting forces on the handlebars throughout the walking. In the force-acceleration mode, the user only needs to accelerate the robot to the desired speed, and then applies small forces on two handlers to maintain the robot's speed, but the robot's response to the input forces is delayed. Besides, it is hard for the user to control the robot's speed accurately. To integrate the advantages of two modes, a new control algorithm is proposed. The control block diagram is shown in Figure 9. Rather than a P (force-velocity mode) or I (force-acceleration mode) controller, a PI controller (other types of controller can also be used) is utilized here to get a fast response to the input forces. And instead of the input force, the error between the input force F_{input} of each handlebar and the desired force $F_{desired}$ is taken as input of the control system. The user only needs to use $F_{desired}$ to drive the robot. And $F_{desired}$ can be set to a preferred small level during walking, so that the user will not feel tired during walking.

During walking, when the user speeds up (V_{user} increases while V_{robot} stays unchanged at this moment), the relative speed between the user and the robot increases ($V_{relative} = V_{user} - V_{robot}$). Then $\Delta X_{body\text{-}robot}$ will become larger. So will the input force F_{input}. The error between the input force F_{input} and the desired force $F_{desired}$ will also get bigger. With the error as input, the PI controller will drive the robot to move faster so as to decrease ΔX_{input} and prevent the input force from increasing until the error between the input force F_{input} and the desired force $F_{desired}$ equals zero. Finally, V_{robot} will be equal to V_{user} and the input force F_{input} will be $F_{desired}$. It functions the same way when the user wishes to slow down. In this way, the robot can adjust its speed automatically

Industrial Robot: An International Journal
Volume 39 · Number 6 · 2012 · 564–579

Figure 7 Walking assisting process in the force-acceleration mode





to keep pace with the user. The user only needs to apply small forces on the handlebars during walking, even in rough terrain. The input forces needed are always $F_{desired}$.

So, as described before, in this mode:

$$\begin{bmatrix} V_{left\,wheel} \\ V_{right\,wheel} \end{bmatrix} = f_{haptic\,interface}\left(\begin{bmatrix} Error_{left\,force} \\ Error_{right\,force} \end{bmatrix}\right) = \left(\begin{bmatrix} F_{left\,input} \\ F_{right\,input} \end{bmatrix} - \begin{bmatrix} F_{left\,desired} \\ F_{right\,desired} \end{bmatrix}\right) * \left((k)_p + k_i * \frac{1}{S}\right) \quad (10)$$

Combining equation (10) with equation (1), we can obtain the system's differential equation of motion:

$$\begin{bmatrix} V_{robot} \\ \omega_{robot} \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{L} & -\frac{1}{L} \end{bmatrix} * \left(\begin{bmatrix} F_{left\,input} \\ F_{right\,input} \end{bmatrix} - \begin{bmatrix} F_{left\,desired} \\ F_{right\,desired} \end{bmatrix}\right) * \left((k)_p + k_i * \frac{1}{S}\right) = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{L} & -\frac{1}{L} \end{bmatrix} * \left(\begin{bmatrix} V_{user} - V_{robot} - V_{left\,arm} \\ V_{user} - V_{robot} - V_{right\,arm} \end{bmatrix} * \frac{1}{S} * k_f - \begin{bmatrix} F_{left\,desired} \\ F_{right\,desired} \end{bmatrix}\right) * \left((k)_p + k_i * \frac{1}{S}\right) \quad (11)$$

The simulation result of a walking process in the comfortable walking mode is shown in Figure 10. In practice, a dead zone is added to ensure that this algorithm will stop working when F_{input} or V_{robot} is smaller than a certain value (which is not used in this simulation, that is why the input force is always 5 N even when the robot stops).

The control flow chart of the comfortable walking mode is shown in Figure 11. Some additional measures are added to ensure the safety of the elderly. For example, when the elderly loses balance during walking and falls towards the robot, the input forces will increase immediately since $\Delta X_{body\text{-}robot}$ increases suddenly. But the robot should not accelerate at this moment. It is not the user's intention. Instead, it is an accident. Thus, when the input forces increase suddenly, it will be treated as an emergency. The robot will decelerate to stop the elderly from falling.

In addition, by modifying the desired forces $F_{desired}$ in Figure 9, force feedback can be realized to help the robot better interact with the user. For example, when an obstacle is detecting, traditionally, the robot will stop suddenly for safety. But it is not a comfortable method to remind the user about the obstacle. While our Walkmate III will warn the user by increasing the desired force $F_{desired}$ (adding a resistance force to $F_{desired}$). The closer the robot to the obstacle is, the bigger $F_{desired}$ will be. In this case, the user will feel it is much more difficult for them to move towards the obstacle. Hence, it can remind the user it is time to make a turn or move back, which is much more comfortable than a sudden stop.

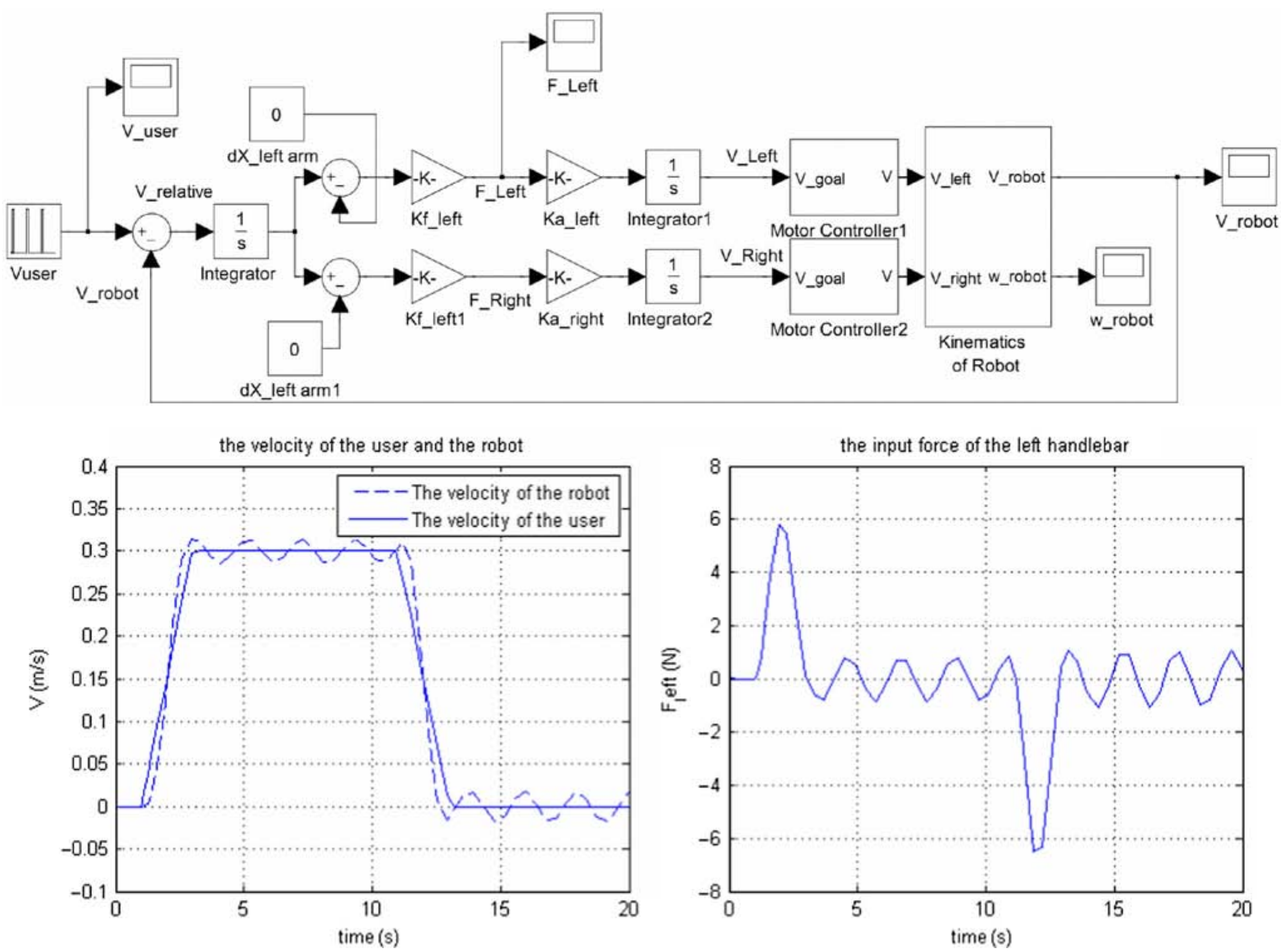
Here a spring-damper model is introduced to generate the resistance force, as shown in Figure 12. When an obstacle is detected at a distance of d in the direction of θ, the resistance force f along the x-axis, is given as:

$$\begin{cases} f = k*(d_{safety-d_x}) + c* - \dot{d}_x, & when\ d_x \le d_{safety} \\ f = 0, & when\ d_x > d_{safety} \end{cases} \quad (12)$$

where k is the virtual spring stiffness, c is the virtual damping coefficient d_{safety} is the original length of the virtual spring and $d_{safety} - d_x$ is the compression of the virtual spring. With $f/2$ on each handlebar, the new desired forces will be:

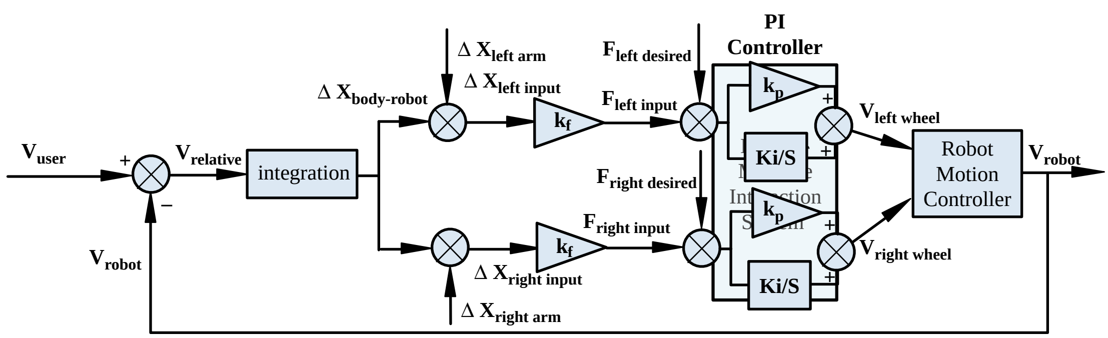
Industrial Robot: An International Journal
Volume 39 · Number 6 · 2012 · 564–579

Figure 8 A simulation result of walking process in the force-acceleration mode with the help of Matlab



Notes: Kf = 180; Ka = 20

Figure 9 Walking assisting process in comfortable walking mode



$$\begin{cases} F'_{left\ desired} = F_{left\ desired} + \frac{f}{2} \\ F'_{right\ desired} = F_{right\ desired} + \frac{f}{2} \end{cases} \qquad (13)$$

With d_x decreases, the resistance force f increases, so is $F'_{desired}$, which means bigger forces are needed to drive the robot forwards. In this way, the robot can remind the user about the obstacle in front of the robot.

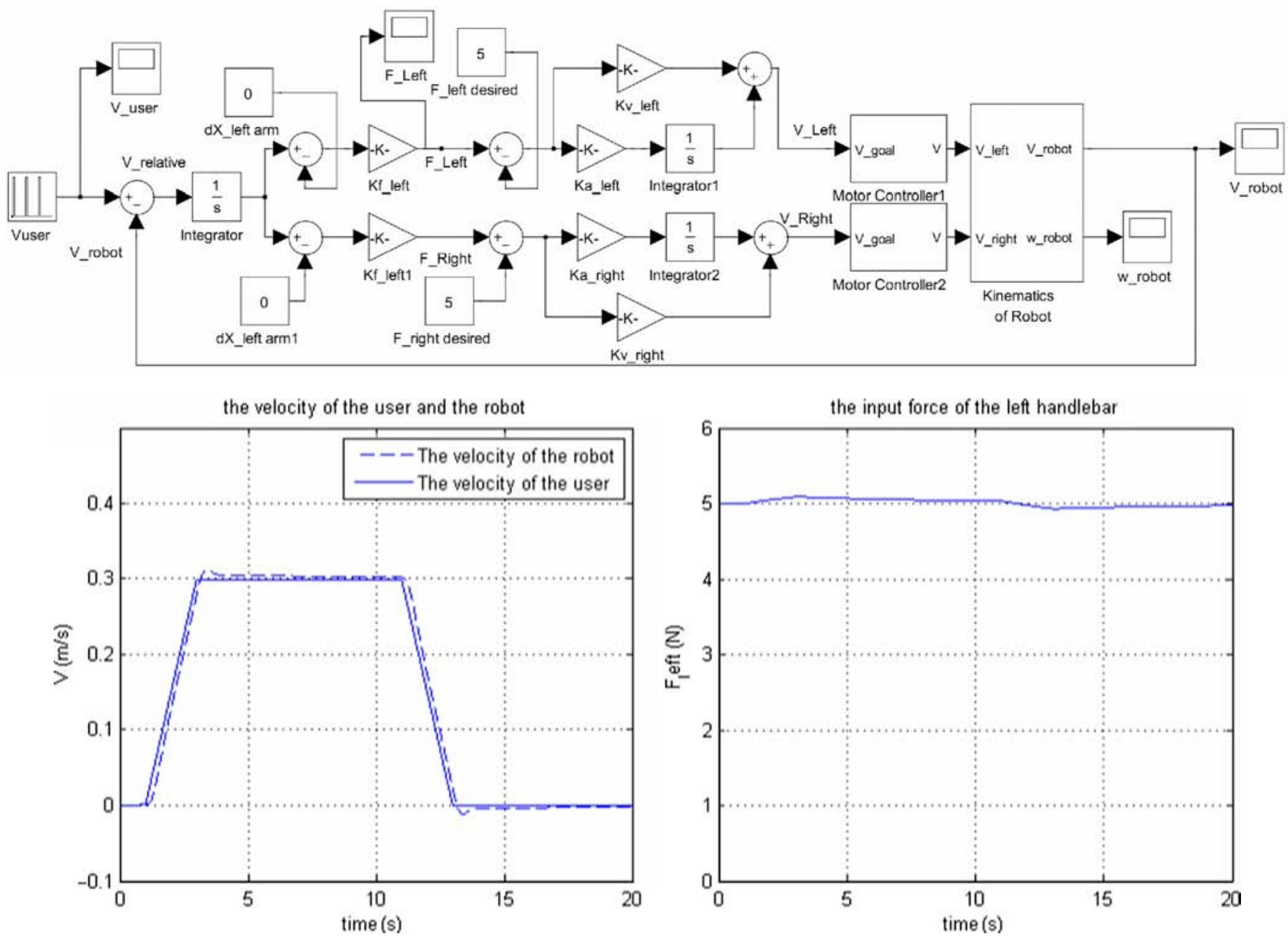
Likely, a virtual torsion spring model is used to generate a steering torque, which can be used to remind the user to change the walking direction. As shown in Figure 12, the obstacle is assumed to be located on the left side of the robot. When it is on the other side, the analysis is also the same. Thus, we have:

$$\begin{cases} M = k'*(\theta_{safety} - \theta) + c'* - \dot{\theta}, \ when \ \theta_{dead\,zone} < \theta \leq \theta_{safety} \\ M = 0, \ when \ \theta > \theta_{safety} \ or \ \theta < \theta_{dead\,zone} \end{cases} \qquad (14)$$

where k' is the stiffness of the virtual torsion spring, c' is the virtual damping coefficient. θ_{safety} is the original angle of the virtual

Industrial Robot: An International Journal
Volume 39 · Number 6 · 2012 · 564–579

Figure 10 A simulation result of walking process in the comfortable walking mode with the help of Matlab



spring and $\theta_{safety} - \theta$ is the compression of the spring. θ_{safety} can be obtained by $\theta_{safety} \geq \arcsin(L_{robot}/2d)$, as shown in Figure 12. When the obstacle is detected right in front of the robot ($\theta < \theta_{dead\,zone}$), no turning around suggestion will be given ($M = 0$), since it is better for the user to decelerate and move back. Hence, the resistance force on each handlebar caused by virtual torsion spring-damper model will be $M/L_{handlebar}$. Finally, combining the effects of two models, we have:

$$\begin{cases} F'_{left\ desired} = F_{left\ desired} + \frac{f}{2} - \frac{M}{L_{handlebar}} \\ F'_{right\ desired} = F_{right\ desired} + \frac{f}{2} + \frac{M}{L_{handlebar}} \end{cases} \quad (15)$$

Evaluation walking experiments

Experimental trials of this walker robot system had been performed at a nursing home in Minhang District, Shanghai, China as part of a research project under the national 863 research program. The same group of elderly people (97 elderly people who were asked to participate in the comfort survey before) took part in this evaluation. In total, 97 elderly people were divided into seven groups (14 people in groups 1-6, and 13 people in group 7). Walkmate III with different control algorithms was used in different groups. All three modes were tested: the force-velocity mode, the force-acceleration mode and the comfortable walking mode. All experiments were carried out inside the nursing home. The participants were asked to walk around with Walkmate III for about 10 min, from one room to another room, from upstairs to downstairs (using an elevator). Then they were asked to evaluate the comfortableness of this walking experience. The result is listed in Table II (Figure 13).

About 85.7 percent (12/14) of group 1 reported that Walkmate III in comfortable walking mode was easy to manipulate and they felt comfort during walking. Here $F_{desired}$ was set to 10 N. In practice, we found that, when the applied force $F_{desired}$ was too small, the elderly people began to feel worried because they felt they were about to lose control of the robot. Thus, the force needed to drive the robot should be small, but cannot be too small. According to the elderly people's preference, $F_{desired}$ should be no smaller than 10 N so that the elderly people will not feel unsafe during walking. All members in group 2 thought it was very uncomfortable to use Walkmate III in the force-velocity mode with $k_v = (0.003(m/s))/N$ because they needed big forces to drive the walker forwards. In group 3, k_v was set to 0.024, 71.4 percent group members thought that walk with help of Walkmate III was comfortable. But when k_v was too bigger (as $k_v = 0.06$ in group 4), some elderly people

Figure 11 The control flow chart of comfortable walking mode

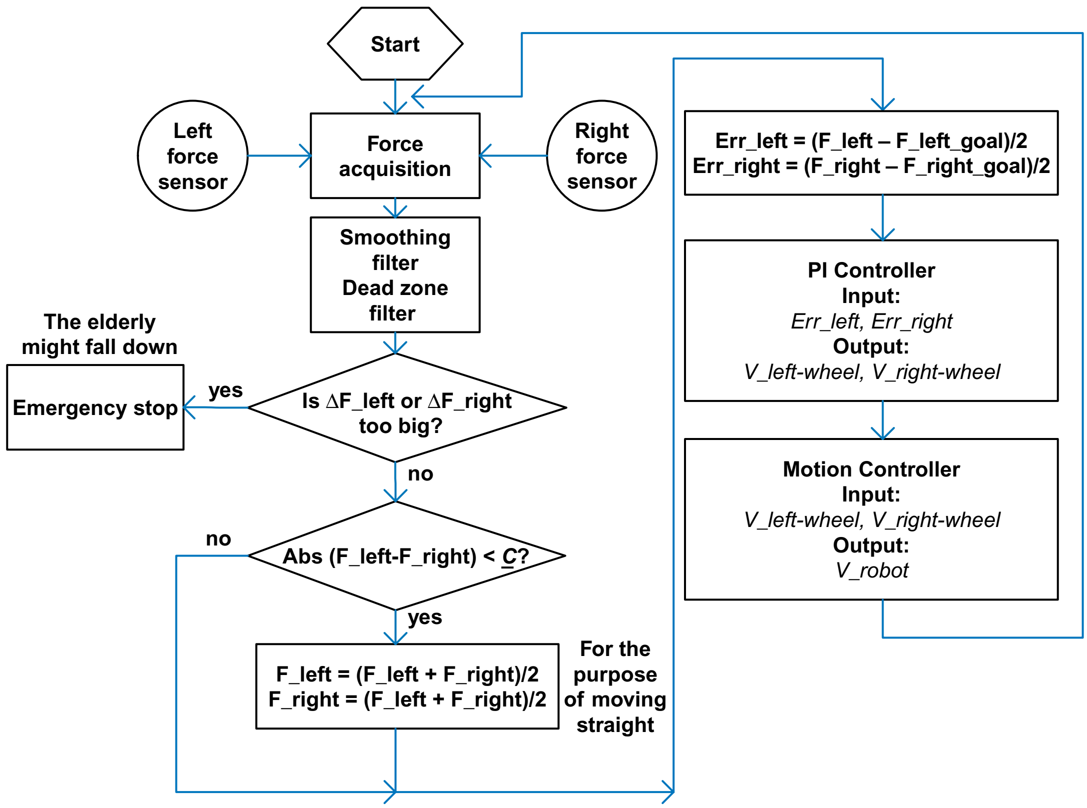


Figure 12 The spring-damper model for obstacle avoiding

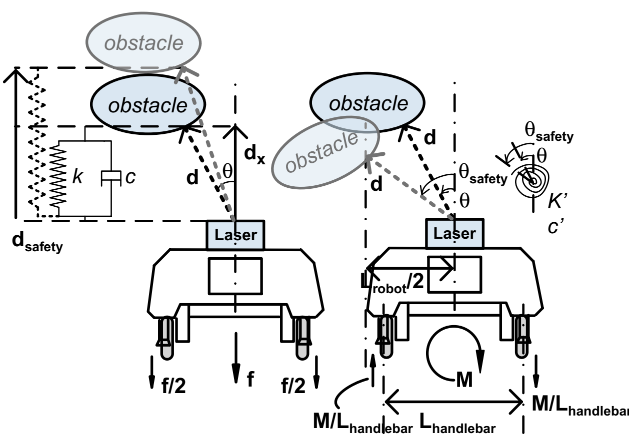


Table II The result of the comfort evaluation

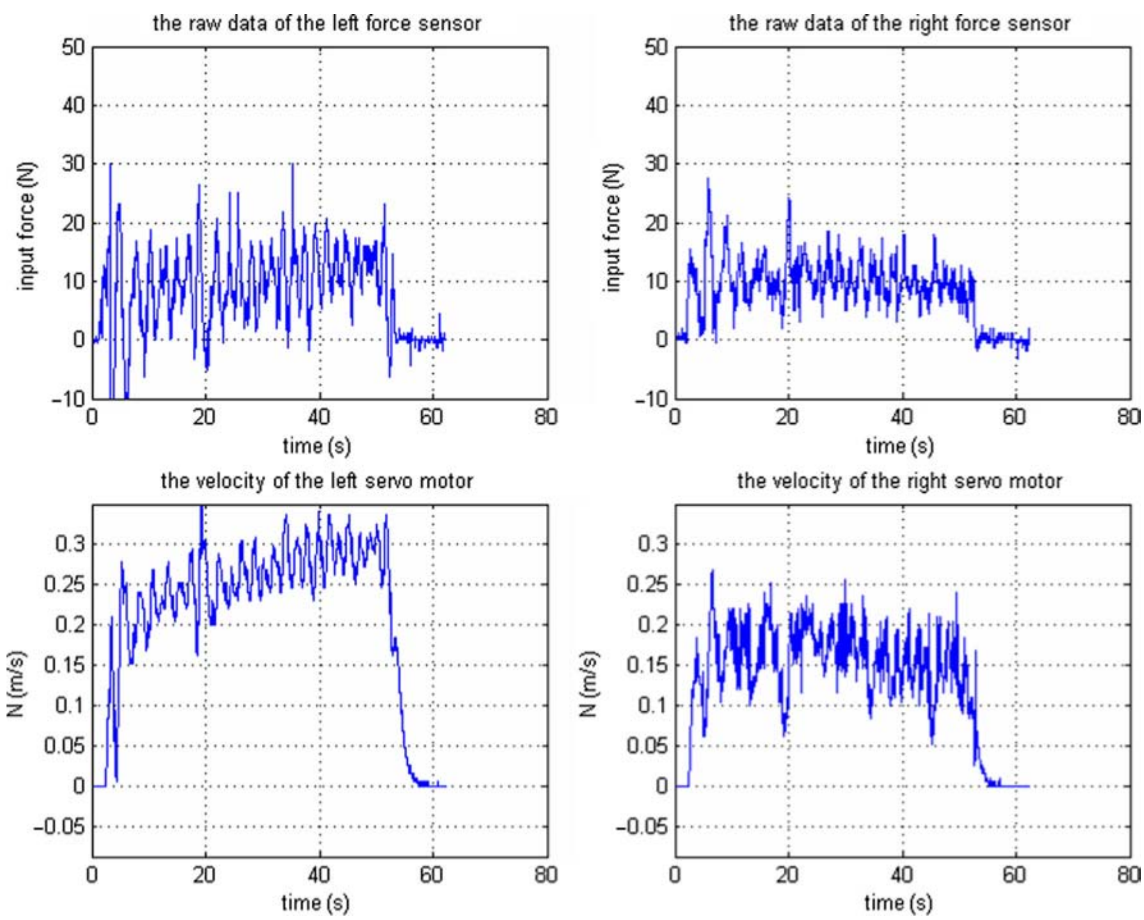
Mode	Parameter(s)	Group	Not comfort (%)	No opinion (%)	Comfort (%)
Comfortable walking mode	$F_{desired} = 10\,N;\ k_p = 0.3,\ k_i = 0.04$	1	0	14.3	85.7
Force-velocity mode	$k_v((m/s)/N) = 0.003$	2	100	0	0
Force-velocity mode	$k_v = 0.024$	3	0	28.6	71.4
Force-velocity mode	$k_v = 0.06$	4	14.3	64.3	21.4
Force-acceleration mode	$k_a(N/(m/s^2)) = 0.5,\ D_a = 0.3$	5	29.9	47.4	22.7
Force-acceleration mode	$k_a = 2,\ D_a = 0.3$	6	64.3	28.6	7.1
Force-acceleration mode	$k_a = 4,\ D_a = 0.3$	7	100	0	0

Figure 13 Experimental trials at a nursing home

began to feel worried because the walker moved too fast even with small forces applied on it. In force-acceleration mode, most elderly felt that the walker was hard to manipulate, especially when k_a was big (as in groups 6 and 7).

Figure 14 shows the raw data of the force sensors and the rotational speed of two wheels during a walk. The control period is 3 ms. As we can see, input forces are always maintained near the desired value ($F_{goal} = 10\,\mathrm{N}$) during walking, which can be adjusted as the user wishes. In about 10 s, the user tries to walk a bit to the right, the velocity of the left wheel increases. But the user still only needs about 10 N to drive the robot. So during the walk, the user will not get the feeling of tired.

Figure 14 Data of sensors in experiment 1: walking forward then turn right



Another walking experiment is shown in Figure 15. In this experiment, an obstacle is detected during walking. A force feedback is then generated to remind the user to turn left.

As contrast experiments, walking experiments in the force-velocity mode and the force-acceleration mode can be examined in Figures 16 and 17. From Figure 16 we can see that, in the force-velocity mode, big forces (even up to 20 N) are always needed to keep the walker moving. The faster the walking speed is, the bigger the needed forces are. In the force-acceleration mode, the user only needs to accelerate the robot when starts to walk, and then applies a small force on the handler to maintain this speed, as shown in Figure 17. But the walker is a little hard to operate. When the user wants to stop in 47 s, it is hard to manipulate the robot to stop immediately.

Conclusion and future work

This paper proposed a novel control algorithm for the walking assistant robot which aims at ensuring user's comfortableness during walking. A theoretical model of the walking assisting process is introduced first and the requirements of comfortable walk are checked with the help of elderly people at a nursing home. Multiple control algorithms' are then examined to evaluate its comfortableness. A new control algorithm, the comfortable walking mode, is designed and implemented in our Walkmate III to offer the user a better comfortableness. In addition, obstacle avoiding strategy of the walking assistant robot is modified. Rather than stop suddenly, a resistance force is generated based on a spring-damper model and feedback to the user when an obstacle is detected, which is also a measure to improve the walking comfortableness.

Experimental trials of our Walkmate III have been performed at the nursing home with successful results. And data of two experiments show that the comfortable walking mode works as expected. But the force data and the velocity data are not so stable. Parameters of the PI controllers in our system have been regulated over and over, but the result does not turn better. We are now focusing on looking for possible causes and replacing the PI controller with other types of controller to achieve a better result. More information can be found in our web site.

Figure 15 Data of sensors in experiment 2: an obstacle is detected during the walk

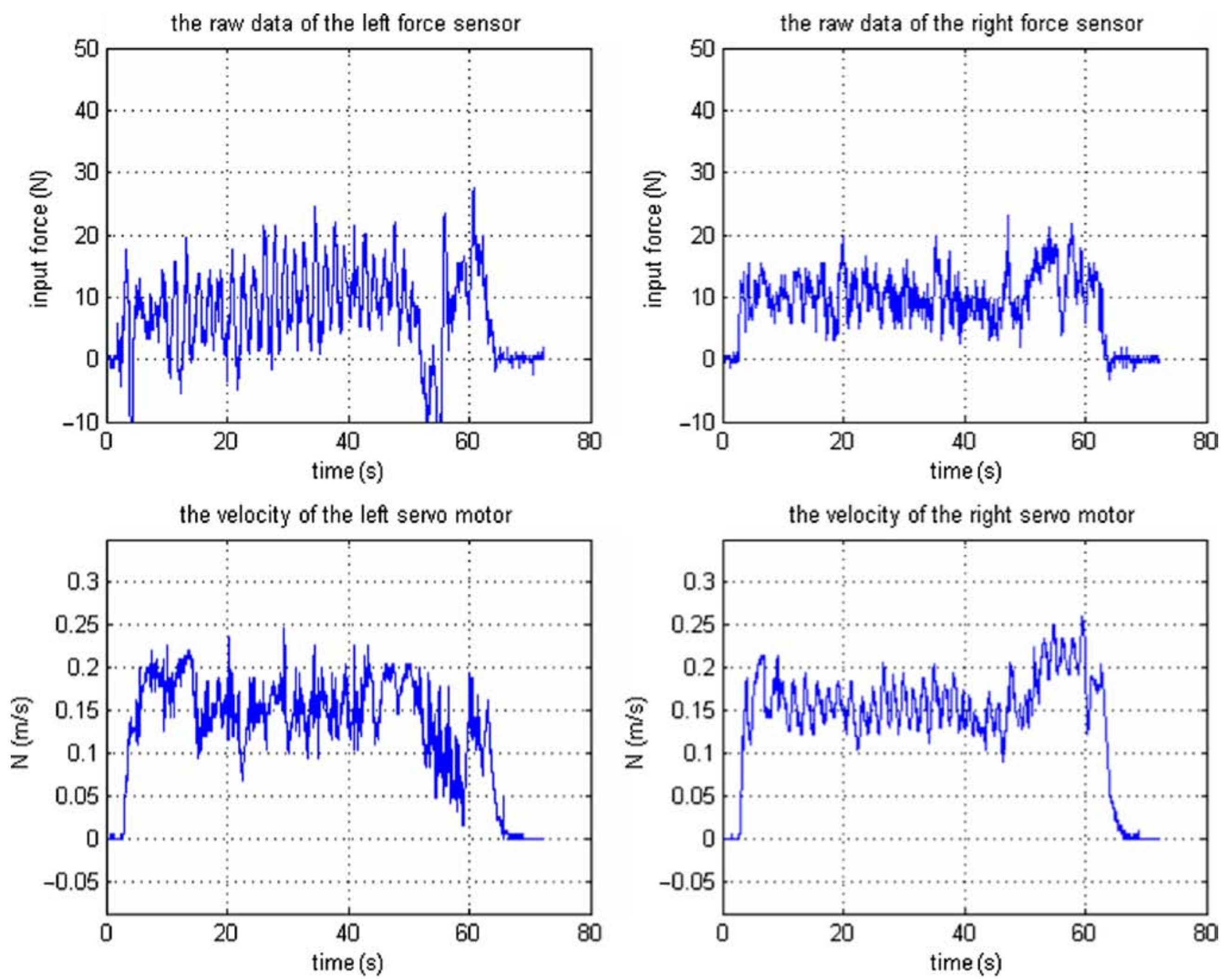


Figure 16 Data of sensors during walking in the force-velocity mode

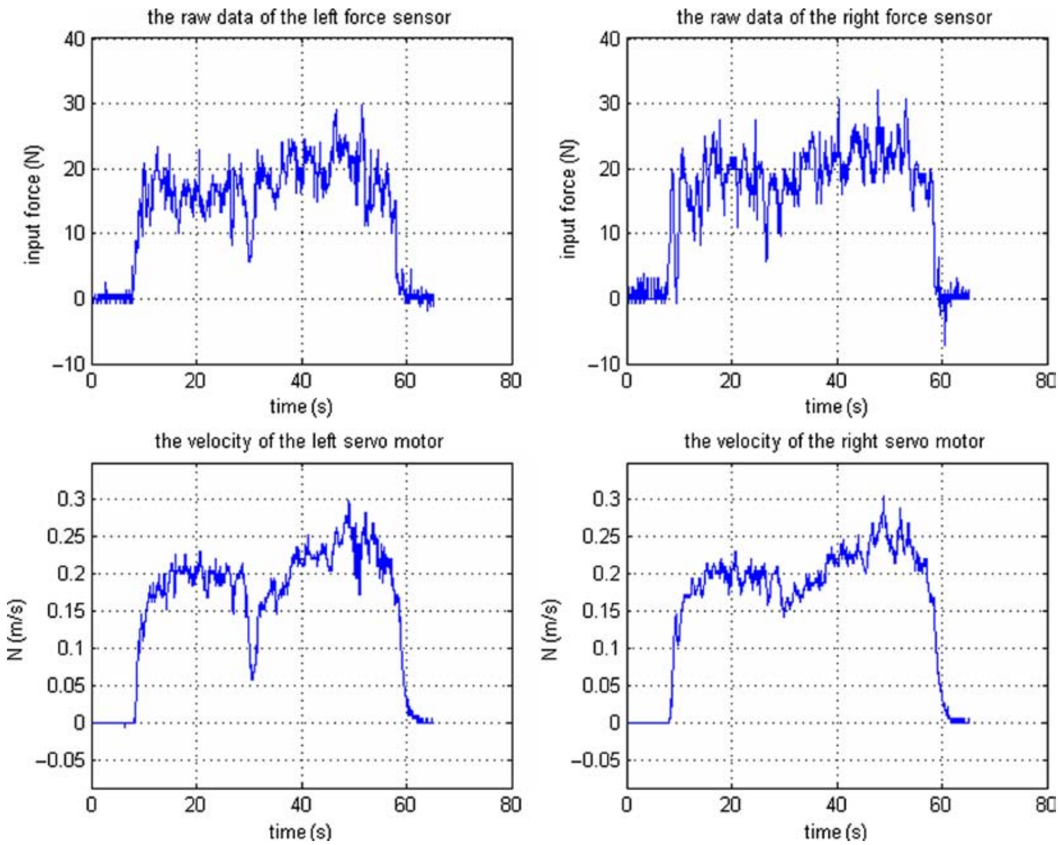
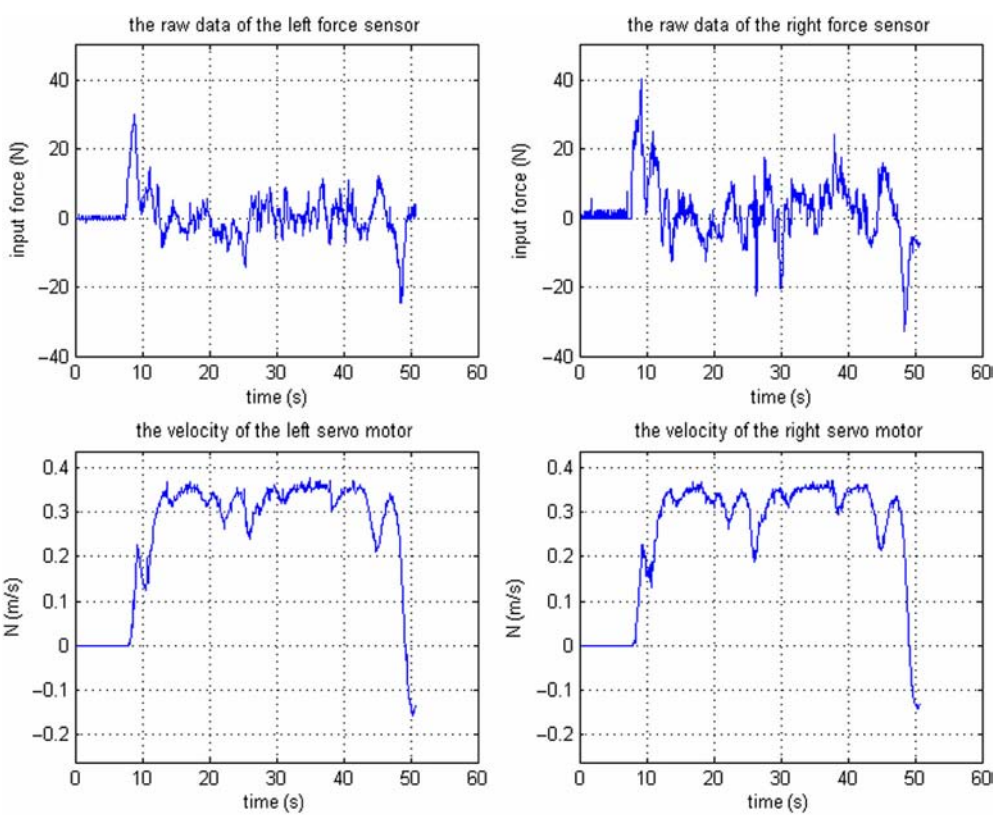


Figure 17 Data of sensors in the force-acceleration mode



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Volume 39 · Number 6 · 2012 · 564–579

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