A Control Approach Based on Passive Behavior to Enhance User Interaction

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***Abstract*—This paper proposes a new control approach for an active (motorized) robotic walking support system based on passive behavior concept. The control approach aims to enhance the interaction between the support system and the user. The passive behavior of a support system allows the user to safely interact with the system since it removes the system's capability to move when there is no user's intention. This passive behavior is realized using imposed apparent dynamics, which uses the user's intention represented by the applied force/torque to derive the system's desired motion. The control approach is extended into a user-oriented motion control algorithm to adapt user's controlling characteristics. This is implemented by varying the point of application of the apparent dynamics. The control approach is further extended to use environment information and realize environment feedback concept. This is implemented by varying the parameters of the apparent dynamics based on environment data. Experimental results are presented to show the validity of the proposed control approach.**

***Index Terms*—Passive behavior, robotic walking support system.**

I. Introduction

ROBOTIC support system will play an important role in our aging society. These systems will address problems due to the continuous increase in elderly population [1], and they can be considered as an external support to stabilize our society. Several robotic support systems have been developed such as elderly-care-robots, personal assistant robots, etc. These systems are used to assist elderly in their daily activities in order to regain independence and improve the quality of their life. Therefore, a control strategy that would allow safe physical interaction between robotic system and human is very important.

In general, robot technology is added to a conventional support system to come up with robotic support system. The advantage of introducing robot technology to a conventional system is the increase in system's high-level functions. This implies that the system can extend its purpose due to the integration of several functions. As an example, conventional walking support system (conventional walker) is used to provide walking stability [2]. With robot technology, the conventional walker can also monitor the health of the user, provide guidance, remind the user when to take his medicine, etc. This is vital to enhance the quality of life of the user. The idea of introducing robot technology to conventional walker leads to the study of robotic walking support system.

Robotic walking support system is used to address one basic elderly problem, which is mobility, and this problem greatly affects elderly independence. Robotic walking support system can be classified into passive and active type. Passive type of robotic walking support system depends on the applied force/torque of the user, and this leads to the support system's inherent safety feature [3]–[6]. Passive support system does not have the capability to move without user's intention. The basic disadvantage of passive type is the load problem. The user handles the weight of the support system, and this leads to a limited high-level function.

An example of a passive type of robotic walking support system is described in [4]. This system uses brakes to change its maneuverability, avoid obstacles, path tracking, etc. The basic characteristics of a passive support system are as follows.

1) User powered: User should push the support system in order to move.
2) Inactive without user's intentions: The support system does not move if there is no intention such as applied force/torque.
3) Actuators are for steering or braking: The actuators in the support system such as motors are used for steering. Some support systems use servo brakes for steering and braking.

Active type of robotic walking support system has motors to drive the system [7]–[10], and this solves the load issue that passive type suffers with. Active type can be augmented with many functions since the mobile base will handle the weight issue of the system. The basic design issue of an active type of robotic walking support system is human–robotic walker interaction. This issue pertains to how we can make the user feel as if he is controlling a passive system, which is safe and stable. The aforementioned design issue will be addressed in designing the proposed control algorithm.

Based on the previous discussion, it is desirable to have a support system with passive characteristics and that can address the load problem to accommodate several high-level functions. Hence, this paper proposes a new control approach for an active robotic walking support system based on passive behavior concept. Passive behavior is used for its safety feature, and it is implemented on an active support system to address the load problem. Fig. 1 shows the potential functions with passive behavior. Although there are several control algorithms with different characteristics, they all possess passive behavior.

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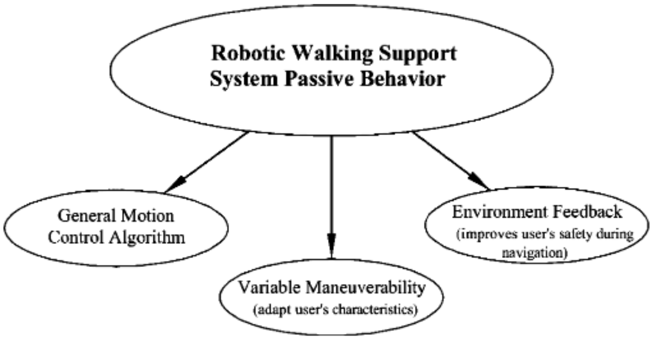


Fig. 1. Robotic walking support system functions with passive behavior.

This study presents a unique idea to control an active robotic walking support system based on passive behavior concept. This control approach allows the user to safely interact with the system since it removes the system's capability to move when there is no user's intention. The passive behavior is implemented by using imposed apparent dynamics, which uses the user's intention represented by force/torque as the control input. The control approach is extended such that the support system can adapt user's controlling characteristics. This is implemented by varying the point of application of the apparent dynamics, which leads to a variable maneuverability of the system.

In addition, the control approach is extended to use environment information. We call this approach as environment feedback, and it is implemented by varying the parameters of the apparent dynamics based on the environment information. The concept of environment feedback is for the robotic support system to sense its environment and change its characteristics to improve the user's safety. As an example situation, assuming there is an obstacle in front of the support system and the intention of the user is to go straight, this situation will endanger the safety of the user. The support system can change its characteristics so that the user will alter his intention to avoid the obstacle.

This paper is organized as follows. Section II will discuss the general motion control algorithm based on imposed apparent dynamics, which possesses passive behavior. Section III will discuss the guidelines in selecting the parameters of the apparent dynamics to satisfy passive behavior. It is important to know if the selected parameters will cause instability to the support system. Section IV will discuss a motion control algorithm based on variable point of application of the apparent dynamics. This is followed by a discussion of a motion control algorithm with environment feedback. Section VI will discuss the experimentation and evaluation of the control algorithm. Lastly, this paper concludes with a brief summary and also discusses the future works.

II. Robotic Walking Support System Motion Control Algorithm With Passive Behavior

Fig. 2 shows the robotic walking support system that is used in this study. This system is an active type of robotic walking support system. It has an omnidirectional mobile base that uses special wheels called "universal wheels," and each wheel is

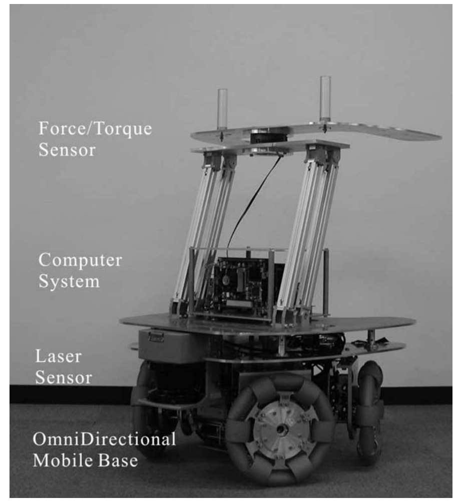


Fig. 2. Active type (motorized) of robotic walking support system with omnidirectional mobile base.

driven by a dc motor. Several sensors are also installed such as force/torque sensor to measure user's intention, laser range sensor to measure environment information, etc. This system is limited to indoor purposes.

The general motion control algorithm of the robotic walking support system based on passive behavior is implemented by using imposed apparent dynamics [9]. This apparent dynamics can be considered as the desired dynamics in which the robotic walking support system behaves based on user's intention. The motion control algorithm is given by (1), and it describes a motion equation of a passive system. The initial conditions of the motion equation are assumed to be zero:

$$\begin{bmatrix} \dot{\varphi} \\ \ddot{\varphi} \end{bmatrix} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ \mathbf{0} & -\mathbf{M}_d^{-1}\mathbf{D}_d \end{bmatrix} \begin{bmatrix} \varphi \\ \dot{\varphi} \end{bmatrix} + \begin{bmatrix} \mathbf{0} \\ \mathbf{M}_d^{-1} \end{bmatrix} \mathbf{F}_h. \quad (1)$$

The output equation is given as

$$y = [0 \quad \mathbf{I}] \begin{bmatrix} \varphi \\ \dot{\varphi} \end{bmatrix} \quad (2)$$

where $\mathbf{M}_d$ and $\mathbf{D}_d \in R^{3\times3}, \mathbf{F}_h \in R^{3\times1}$, and $\varphi = [x \ y \ \theta]^T$. $\mathbf{M}_d$ and $\mathbf{D}_d$ are the desired inertia and damping matrices, respectively. $\mathbf{F}_h$ is the user's intention represented by the applied force/torque to the robotic walking support system. The structure of $\mathbf{M}, \mathbf{D}$, and $\mathbf{F}_h$ are given by (3)–(5), respectively:

$$\mathbf{M} = \begin{bmatrix} M_x & 0 & 0 \\ 0 & M_y & 0 \\ 0 & 0 & M_z \end{bmatrix} \quad (3)$$

$$\mathbf{D} = \begin{bmatrix} D_x & 0 & 0 \\ 0 & D_y & 0 \\ 0 & 0 & D_\theta \end{bmatrix} \quad (4)$$

$$\mathbf{F}_h = \begin{bmatrix} F_x \\ F_y \\ N_z \end{bmatrix}. \quad (5)$$

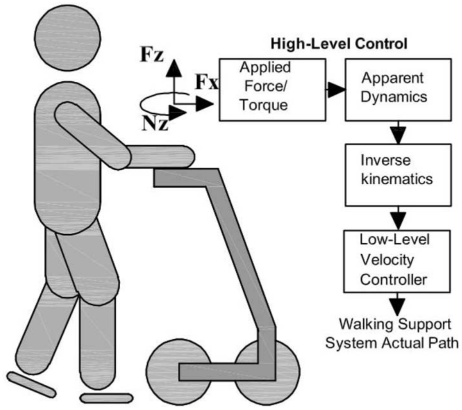


Fig. 3. General motion control diagram of the robotic walking support system in implementing passive behavior emulation.

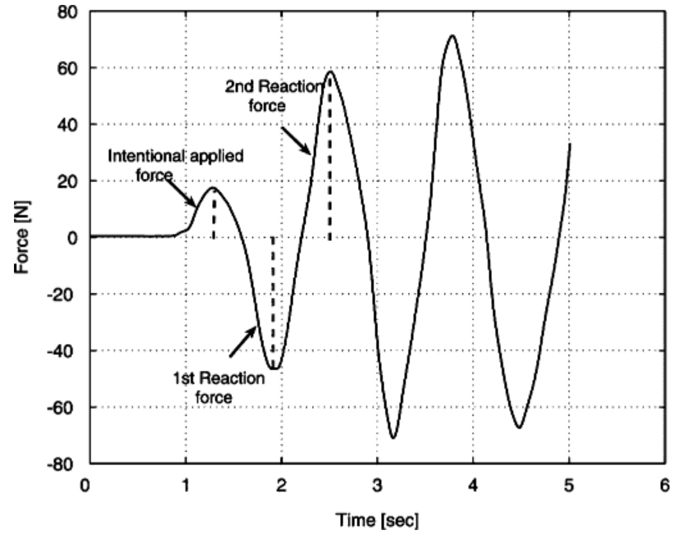


Fig. 4. Oscillations due to reaction force when arms are fully extended.

Fig. 3 shows the fundamental control block diagram of the robotic walking support system. The user's intention represented by applied force/torque is passed to the apparent dynamics to determine the desired states of the system (velocity and position). Based on the inverse kinematic equation of the system, each desired wheel velocity is determined, and this is passed to a low-level motion controller for regulation.

The previous discussion gave a good overview on how the system is controlled. The general motion control algorithm is simple but excellent in handling physical interaction between a human and a robot. Section II is important for the succeeding section since we will be modifying the general motion control algorithm to implement user adaptive control and environment feedback with passive behavior.

III. Parameter Guideline in Satisfying Passive Behavior

In the previous section, we presented the motion control algorithm with passive behavior, and this is based on imposed apparent dynamics. It is very important that the parameters of the apparent dynamics do not cause instability to the support system, and thereby, violate the passive characteristics. Yu *et al.* [11] mentioned that there are values of the apparent dynamics that lead the system into instability, but the detailed analysis on the cause of oscillation is not discussed.

The oscillation normally happens when the user applies an intentional force to the system, and due to inertial mass, creates a reaction force that is opposite to the intentional force. The reaction force makes the system move backward, and when the system is near the user, again a reaction force is experienced, which will move the system forward. Hence, an oscillation occurs and the reaction force expands in time. Meer *et al.* [12] discussed the stability of flexible-object impedance controller when coupled to an arbitrary passive environment. A guideline was developed to ensure coupled system stability. It is important that the system is stable based on the selected parameters.

To illustrate the aforementioned problem, Fig. 4 shows the force read by the force/torque sensor during oscillation. This situation endangers the safety of the user, and it implies that a parameter guideline is needed to ensure the stability of the system. Let us consider a one-dimensional control for the support system, as shown in Fig. 5, and its motion control algorithm is given by

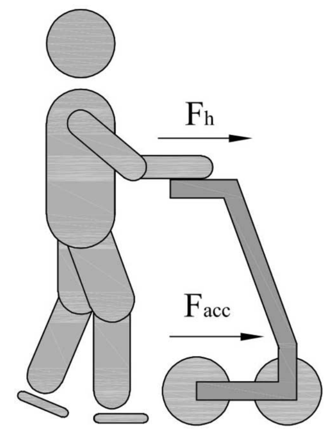


Fig. 5. Support system diagram with user applied force and actuator force.

$$M_d\ddot{x} + D_d\dot{x} = F_h \tag{6}$$

where M_d and D_d are the desired mass and damping parameters, respectively. F_h is the applied force of the user. The initial conditions are assumed to be zero.

The actual motion equation is described as

$$M_a\ddot{x} = F_h + F_{\rm acc} \tag{7}$$

where M_a is the actual mass. F_h and $F_{\rm acc}$ are the applied force of the user and the actuator force of the system, respectively. Based on (6), the desired acceleration of the system in S-domain is given by

$$a_{x_d}(s) = \frac{F_h(s)}{M_d + (\frac{D_d}{s})}. \tag{8}$$

Substituting (8) into (7) leads to the relationship between the actuator force F_{acc} and user applier force F_h. It is given by

$$\frac{F_{\text{acc}}(s)}{F_h(s)} = \frac{M_a - M_d}{M_d}\left(\frac{s - \frac{D_d}{M_a - M_d}}{s + \frac{D_d}{M_d}}\right). \tag{9}$$

Equation (9) can also be written as

$$G(s) = a\frac{s-b}{s+c} \tag{10}$$

where, and c are given as $a = (M_a - M_d)/M_d, b = D_d/(M_a - M_d)$, and $c = D_d/M_d$, respectively.

The relationship between the actuator force and the user's applied force is given in (9). When the arms are fully extended, a reaction force at the handle is generated. This can be considered as a negative feedback since the reaction force is opposite to the applied force. We can solve the closed-loop poles of the system, but the result leads to a pole around zero, which means that the system is marginally stable. This does not explain why in actual situations there are values of the desired mass in which the system is stable. The other approach is to consider the reaction force as an input. This leads to a positive feedback setup, and it will show that some values of the desired mass leads to a stable system. It will also show that low values of the desired mass lead the system into instability.

It is mentioned in [12] that when the value of the desired mass is low, the system is unstable. In addition, it is mentioned that if the desired mass is one fourth of the actual mass, the system is unstable. Another approach to stabilize the unstable system due to low desired mass value is to introduce a block $G_c(s)$:

$$G_c(s) = K. \tag{11}$$

Therefore, the open-loop transfer function of the system is given by

$$G_c(s)G(s) = K\left(a\frac{s-b}{s+c}\right). \tag{12}$$

Based on the selected value of M_d and D_d, K is selected such that the system is stable. We mentioned that if the desired mass is almost equal to the actual mass, the system is stable, but this is undesirable since, in general, the actual mass is heavy. It is more practical to look for solutions that will stabilize the system due to low value of the desired mass.

IV. Control Based on Relocated Center of Application With Passive Behavior

The general motion control-algorithm-based apparent dynamics was presented in Section II. The apparent dynamics is imposed on an arbitrary point O_{coa}, where "coa" means *center of application*. It is assumed that the origin of the robot coordinate, represented as O_r, coincides with O_{coa} ($O_{\text{coa}} = O_r$). This section will consider the motion control algorithm based on apparent dynamics, but the center of application O_{coa} does not coincide with $O_r (O_{\text{coa}} \neq O_r)$.

The application of the aforementioned control approach is shown in Fig. 6. A user is given a desired path, but due to some controlling disability, the user's actual path deviates from the desired path, as shown in Fig. 6(a). Hence, it is possible to cancel the unwanted intention by relocating the center of application of the apparent dynamics. Fig. 6(b) illustrates this concept, and based on the relocated center of application, it is possible that the user can track the desired path. The approach in relocating the center of application changes the maneuverability of the support system. In case we vary the point of application of the apparent dynamics, it leads to a variable maneuverability system.

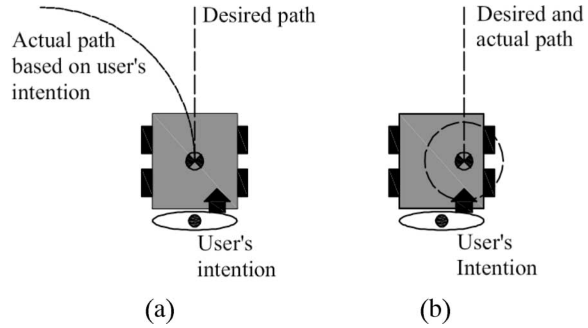


Fig. 6. Concept of relocating the point of application of apparent dynamics to adapt user's controlling characteristics.

The steps in implementing the control approach with relocated center of application are:

1) determination of user's intention represented by applied force/torque (${}^r\mathbf{F}_h = [{}^rF_x\ {}^rF_y\ {}^rN_z]^T$).
2) transformation of applied force/torque to the new apparent dynamics center of application O_{coa}

$$^{\text{coa}}\mathbf{F}_h = {}^{\text{coa}}\mathbf{T}_r(X_{\text{coa}}, Y_{\text{coa}})^r\mathbf{F}_h \tag{13}$$

$$^{\text{coa}}\mathbf{T}_r(X_{\text{coa}}, Y_{\text{coa}}) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ Y_{\text{coa}} & -X_{\text{coa}} & 1 \end{bmatrix}. \tag{14}$$

3) velocity determination at the new center of application of the apparent dynamics $[{}^{\text{coa}}v_x\ {}^{\text{coa}}v_y\ {}^{\text{coa}}\dot{\theta}]^T$.
4) velocity transformation from the new center of application to the origin of the robot coordinate frame $[{}^rv_x\ {}^rv_y\ {}^r\dot{\theta}]^T$

$$\begin{bmatrix} {}^rv_x \\ {}^rv_y \\ {}^r\dot{\theta} \end{bmatrix} = {}^{\text{coa}}\mathbf{T}_r(X_{\text{coa}}, Y_{\text{coa}})^T \begin{bmatrix} {}^{\text{coa}}v_x \\ {}^{\text{coa}}v_y \\ {}^{\text{coa}}\dot{\theta} \end{bmatrix} \tag{15}$$

5) regulation of robot's desired velocities.

Based on (13) and (14), the torque is changed at the new center of application of the apparent dynamics O_{coa}. Since torque is highly correlated to the heading angle of the support system, the approach of relocating the center of application of the apparent dynamics can be used to cancel unintentional torque. In addition, users who cannot properly steer their support system can be aided by varying the center of application of the apparent dynamics. This approach leads to a variable maneuverability of the system, and it is passive since, without user's intention, the system will not move.

Training is introduced in order to determine a new $(X_{\text{coa}}, Y_{\text{coa}})$ based on user's controlling characteristics. A training path can be given to a user, and it can be a semicircle path with radius R_k [9]. Environment information such as wall orientation can also be used to adjust the center of application [13]. In general, to follow a semicircle training path (TP_k), the velocity along X-axis of the support system should be equal to the angular velocity of the system times the path radius. This can be represented by

$$^{r}v_x = R_k\ {}^{r}\dot{\theta}. \tag{16}$$

The velocities $^{r}v_x$ and $^{r}\dot{\theta}$ are independent, and the objective of training is to determine a new Y_{coa} such that the condition given in (16) is satisfied. At steady state, the linear and angular velocities of the support system are described by

$$^{\text{coa}}v_x = \frac{^{\text{coa}}F_x}{D_x}, \qquad {}^{\text{coa}}\dot{\theta} = \frac{^{\text{coa}}N_z}{D_\theta} \tag{17}$$

where $^{\text{coa}}N_z$ is

$$^{\text{coa}}N_z = {}^{r}N_z + Y_{\text{coa}}\ {}^{r}F_x. \tag{18}$$

One assumption to this approach is that the user just pushes the support system and the system varies the center of application to follow the path. It is assumed that lateral force is not applied. Based on step 4) and the relationship described in (16), the resulting Y_{coa} is given by

$$Y_{\text{coa}_i} = \frac{-\left[\frac{^{r}N_{z_i}}{^{r}F_{x_i}} - R_k\right]}{2} \pm \frac{\sqrt{\left(\left(\frac{^{r}N_{z_i}}{^{r}F_{x_i}}\right) - R_k\right)^2 - 4\left(\left(\frac{D_\theta}{D_x}\right) - R_k\left(\frac{^{r}N_{z_i}}{^{r}F_{x_i}}\right)\right)}}{2}. \tag{19}$$

In case the user applies force only along X-axis and $^{r}N_z = 0$, the resulting Y_{coa} is described by

$$Y_{\text{coa}} = \frac{R_k \pm \sqrt{R_k^2 - 4\left(\frac{D_\theta}{D_x}\right)}}{2}. \tag{20}$$

For straight line training path, Y_{coa} is given by

$$Y_{\text{coa}_i} = -\frac{N_{z_i}}{F_{x_i}}. \tag{21}$$

Based on the previous discussion, the resulting equation of motion of the robotic walking support system with variable maneuverability is given in (22). X_{coa} is assumed to be at the origin of the coordinate system attached to the support system. This is due to the assumption that the user just pushes the system and lateral applied force is zero.

$$\mathbf{M}\ddot{\varphi} + \mathbf{D}\dot{\varphi} = {}^{\text{coa}}\mathbf{T}_r(X_{\text{coa}}, Y_{\text{coa}})^{r}\mathbf{F}_h. \tag{22}$$

V. Environment Feedback With Passive Behavior

The capability of a support system to feed back the environment information to its user is an important feature to enhance interaction. It can be employed to inform users about the danger in the subsequent environment. In this study, we concentrate on changing the motion behavior of the system as a way of sending message to the user. As an example, if there is an obstacle in the heading direction of the support system and the user, the system can change its behavior such that it will be hard to push in the direction of the obstacle. This approach will allow the user to change his applied intentions to avoid the danger, and it will improve the user's safety during navigation. With environment feedback, a closed loop between the environment and the support system user is created.

The approach we consider in implementing the environment feedback is to include the environment information in the motion control algorithm. It will be of great interest if the support system can sense its environment and change its motion characteristics to improve the user's safety. The unique idea that is presented in this paper is an environment feedback that yields a passive behavior for an active (motorized) walking support system. This means that without user's intention, which is represented by applied force/torque, the system will not move.

Environment feedback is implemented by using repulsive force concept. An environment element such as an obstacle creates a repulsive field [15], and a repulsive force is derived from the field. The generated force is augmented in the motion control algorithm, and this alters the direction in which the support system is headed. This approach is illustrated and implemented in [4] and [14]. Assuming that we will use the motion equation based on imposed apparent dynamics discussed in Section II, the resulting motion control algorithm with environment feedback is given in (23). This equation is reasonable to cancel user's intention when an environment element is detected such as an obstacle in the navigating path:

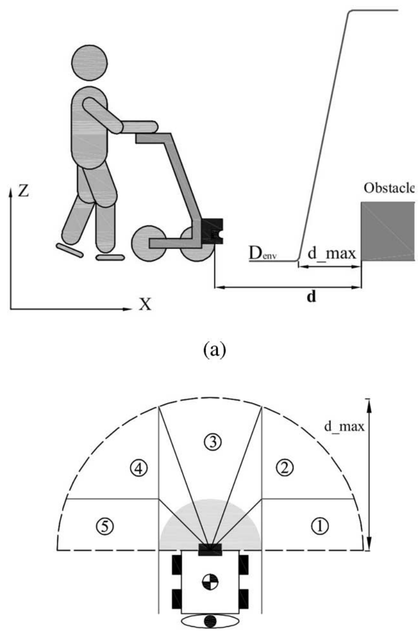
$$\mathbf{M}\ddot{\varphi} + \mathbf{D}\dot{\varphi} = \mathbf{F}_h + \mathbf{F}_{\text{env}}. \tag{23}$$

The disadvantage of the aforementioned approach is that there is a possibility for the system to move without user's intention, and this is a special case for an active (motorized) walking support system. Based on (23), the user's intention will be altered due to the added force. As an example, the user wants to go straight, but due to an environment element in front of the support system, it is possible that the system will move to a different direction. In addition, when the user accidentally releases the system, this leads to $\mathbf{F}_h = \mathbf{0}$. The resulting equation of the support system is given as

$$\mathbf{M}\ddot{\varphi} + \mathbf{D}\dot{\varphi} = \mathbf{F}_{\text{env}}. \tag{24}$$

The generated force due to an environment element $\mathbf{F}_{\text{env}}$ will cause some motion to the support system. The aforementioned situation endangers the safety of the user since the presence of the environment element, which causes a repulsive force, will make the system move without user's intention (applied force/torque). This violates the passive behavior characteristics. Hence, we propose an approach to feedback environment information such that its effect is passive for an active (motorized) type of walking support system. The proposed approach will not alter the intentional direction of the user, but will only allow the user to feel the existence of the environment element.

In Section II, we discussed the general motion equation, and it is given by (1). This equation is modified to include environment information with passive behavior. The resulting equation is



(a)

(b)

Fig. 7. (a) Concept of variable apparent dynamics based on environment information. (b) Sensor data segmentation.

given by

$$(\mathbf{M}+\mathbf{M}_{\rm env})\ddot{\varphi}+(\mathbf{D}+\mathbf{D}_{\rm env})\dot{\varphi}=\mathbf{F}_h \tag{25}$$

where $\mathbf{M}_{\rm env}$ and $\mathbf{D}_{\rm env} \in \mathrm{R}^{3\times 3}$. Both these matrices are positive semidefinite. $\mathbf{M}_{\rm env}$ will be derived based on $\mathbf{D}_{\rm env}$ to maintain the system bandwidth.

Fig. 7(a) illustrates the effect of an environment element as an obstacle to the damping parameter of the apparent dynamics. Based on (25), the parameters are designed such that they will have positive values and will not cancel the base parameters ($\mathbf{M}$ and $\mathbf{D}$). There is a need to segment the sensor region such that an environment element ($\varepsilon_{\rm env}$) in a certain region can affect only a particular direction. Fig. 7(b) shows the segmented sensor region $\mathbf{SR}=\{\mathrm{SR}_1,\mathrm{SR}_2,\ldots,\mathrm{SR}_5\}$, and each region will affect different damping parameters. As an example, SR_3 will affect $D_{{\rm env}_x}$, SR_1 and SR_5 will affect $D_{{\rm env}_y}$, and SR_2 and SR_4 will affect $D_{{\rm env}_\theta}$. Equation (26) defines $D_{{\rm env}_x}$

$$D_{{\rm env}_x}=\begin{cases}\xi_x\left(\dfrac{d_{{\rm max}_x}-d_x}{d_{{\rm max}_x}}\right), & \text{if } \varepsilon_{\rm env} \text{ in region 3} \\ & \varepsilon_{\rm env} \text{ is environment element} \\ 0, & \text{otherwise.}\end{cases} \tag{26}$$

$D_{{\rm env}_y}$ is given by

$$D_{{\rm env}_y}=\begin{cases}\xi_y\left(\dfrac{d_{{\rm max}_y}-d_y}{d_{{\rm max}_y}}\right), & \text{if } \varepsilon_{\rm env} \text{ in region 1 and } F_y<0 \\ \xi_y\left(\dfrac{d_{{\rm max}_y}-d_y}{d_{{\rm max}_y}}\right), & \text{if } \varepsilon_{\rm env} \text{ in region 5 and } F_y>0 \\ 0, & \text{otherwise.}\end{cases} \tag{27}$$

For an environment element affecting the steering of the support system, it should be in regions 2 and 4. The parameter design of $D_{{\rm env}_\theta}$ should consider the distance and the angle of the environment element with respect to the support system. $D_{{\rm env}_\theta}$ is (28) and it is shown at the bottom of the page. In (26), (27), and (28), ξ_x, ξ_y, ξ_θ are constants.

We should consider that the steady-state velocity of the apparent dynamics is given by $(\mathbf{D}+\mathbf{D}_{\rm env})^{-1}\mathbf{F}_h$. This implies that increasing $\mathbf{D}_{\rm env}$ will increase the required force to maintain the user's desired velocity. The increase in required applied force is the key to environment feedback. The user will feel the resistance of the system in the existence of environment element that will endanger his safety.

VI. Experimentation

This section will discuss the implementation and evaluation of the motion control algorithm based on passive behavior. The concept shown in Fig. 1 such as the implementation of general motion control algorithm, variable center of application of the apparent dynamics, and environment feedback are integrated into a single motion equation given by

$$\underbrace{(\mathbf{M}+\mathbf{M}_{\rm env})\ddot{\varphi}+(\mathbf{D}+\mathbf{D}_{\rm env})\dot{\varphi}}_{\text{environment feedback}}=\underbrace{{}^{\rm coa}\mathbf{T}_r(X_{\rm coa},Y_{\rm coa})\mathbf{F}_h}_{\substack{\text{variable center}\\ \text{of application}}}. \tag{29}$$

The left-hand side of (29) represents the environment feedback, which aims to improve the user's safety during navigation. The right-hand side of the motion equation represents the variable maneuverability of the system by changing the point of application of the apparent dynamics. This is used to adapt user's controlling characteristics.

The experiments in stability, relocated center of application of apparent dynamics, and environment feedback are all carefully observed and monitored for the safety of the users. Based on the power rating of the robotic walking support system, we are required by the university to have a monitoring group, which observes and evaluates the experiments. The members of the group are researchers in our laboratory. One basic function of

$$D_{{\rm env}_\theta}=\begin{cases}\xi_\theta\left(\left(\dfrac{d_{{\rm max}_\theta}-d_\theta}{d_{{\rm max}_\theta}}\right)+\left(\dfrac{\theta_{\rm max}-|\,\theta\,|}{\theta_{\rm max}}\right)\right), & \\ & \text{if } \varepsilon_{\rm env} \text{ in region 2 and } N_z<0 \\ \xi_\theta\left(\left(\dfrac{d_{{\rm max}_\theta}-d_\theta}{d_{{\rm max}_\theta}}\right)+\left(\dfrac{\theta_{\rm max}-|\,\theta\,|}{\theta_{\rm max}}\right)\right), & \\ & \text{if } \varepsilon_{\rm env} \text{ in region 5 and } N_z>0 \\ 0, & \text{otherwise.}\end{cases} \tag{28}$$

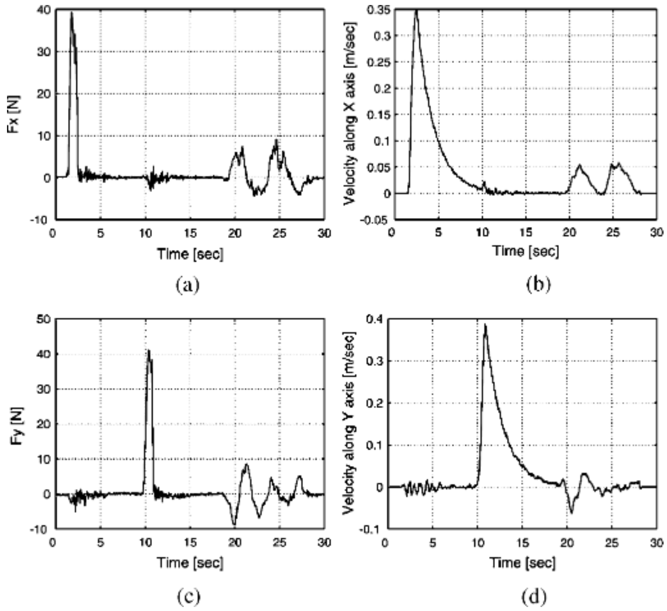


Fig. 8. Applied intention and response of the robotic walking support system with passive behavior.

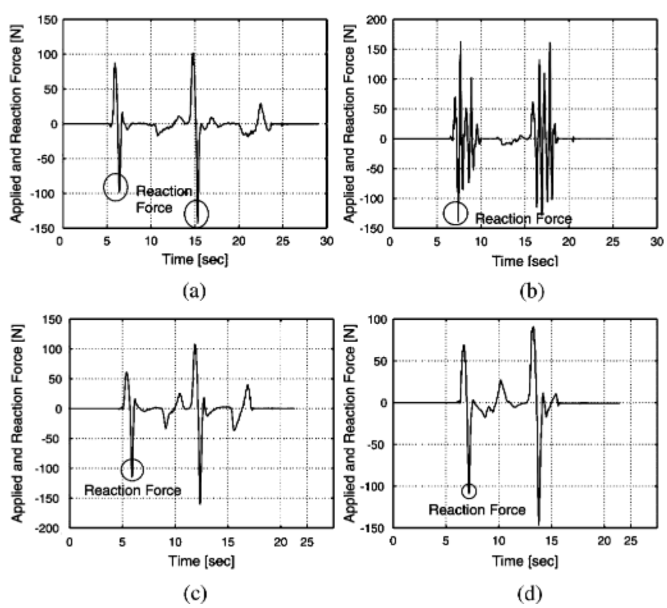


Fig. 9. Apparent dynamics parameter evaluation for different values of M_d and D_d. (a) $M_d = 60, D_d = 30$. (b)$M_d = 20, D_d = 30$. (c) $M_d = 60, D_d = 10$. (d) $M_d = 60, D_d = 5$.

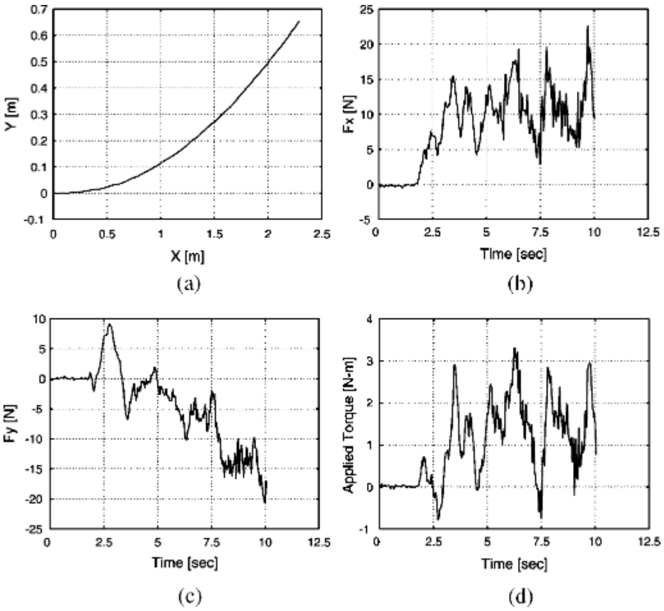


Fig. 10. Trajectory of the support system and user's intention.

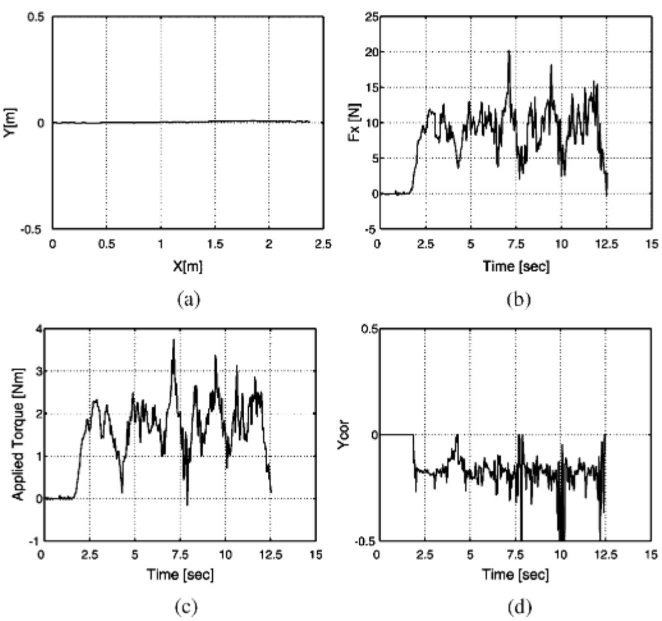


Fig. 11. Control of the support system with relocated apparent dynamics center of application.

the group is to shutdown the system if they feel that the safety of the user is endangered.

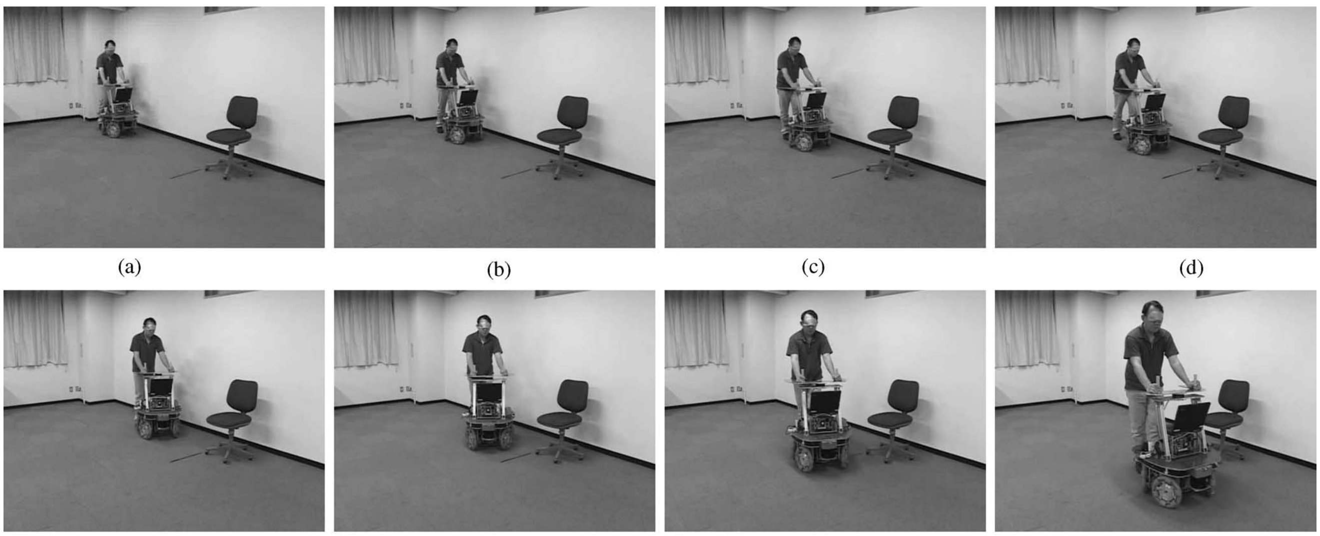
A. Evaluation of General Motion Control Algorithm With Passive Behavior

The general motion control algorithm of the support system is evaluated by applying some intentional force, and the resulting response is logged and evaluated. Fig. 8(a) shows the applied force to the support system and Fig. 8(b) shows the resulting velocity response. It can be observed that the system accelerates, and when the applied force becomes zero, the velocity of the system starts to decay. The evaluation is also done along Y-axis, as shown in Fig. 8(c) and (d). The velocity response shown in Fig. 8(b) and (d) shows a typical behavior of a passive system, and this implies that passive behavior for active robotic support system is successfully implemented by using the apparent dynamics.

The intention of the next experiment is to evaluate the stability of the system. Users were instructed to move the system until the arms are fully extended, and reaction force is normally

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

Fig. 12. Environment feedback concept for active support system. The environment element information changed the parameters of the motion control algorithm.



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

(e) (f) (g) (h)

Fig. 13. User's intention represented by applied force/torque and the corresponding damping parameter due to environment element.

experienced due to inertial mass of the system. In case the selected parameters lead to oscillation, the users were instructed to stop applying intentions or just release the system.

The stability of the apparent dynamics is evaluated by considering several values of M_d and D_d. The actual mass of the support system is about 80 kg, and based on Section III, the system is stable if M_d (desired mass) is near the actual value. Fig. 9(a) shows the applied and reaction forces for $M_d = 60$ and $D_d = 30$. This figure clearly shows that the system is stable. Fig. 9(b) shows the applied and reaction forces for $M_d = 20$ and $D_d = 30$. The response of the system shows some oscillations, and this endangers the safety of the user. Fig. 9(c) and (d) shows the response of the system for low damping values, and these figures show that the response of the system is still stable. Fig. 9(c) and (d) shows that the main cause of instability is the low desired mass values.

B. Evaluation of Apparent Dynamics Relocated Center of Application With Passive Behavior

The motion control algorithm in adapting user's controlling characteristic based on relocated center of application is evaluated based on the desired path followed. The user is asked to follow a desired path, which is represented by a straight line. Based on Fig. 10(a), the user is unable to follow the desired path. Fig. 10(b)–(d) shows the user's intention, and it can be observed that there is unintentional applied force along Y-axis and torque along Z-axis. The effect of the unintentional torque can be suppressed by relocating the center of application of the apparent dynamics, and the effect of the unintentional force along Y-axis can be removed by increasing the damping parameter along Y-axis.

Another trial is conducted by using relocated center of application, and Fig. 11(b) and (c) shows the user's applied intention and Fig. 11(d) shows the corresponding Y_{coa} during the trial. Fig. 11(a) shows the trajectory of the user with relocated center of application, and it clearly shows that the user successfully follows the desired path even with the existence of unintentional torque. The success in trajectory following was done by changing the maneuverability of the support system, and this approach is one way to adapt the user's controlling characteristics. The control approach has passive behavior since the system does not move without user's intention.

C. Evaluation of Environment Feedback With Passive Behavior

The environment feedback with passive behavior is implemented by changing the parameters of the motion control algorithm. This approach allows the system to be inactive without user's intention. The concept is shown in Fig. 12. As the

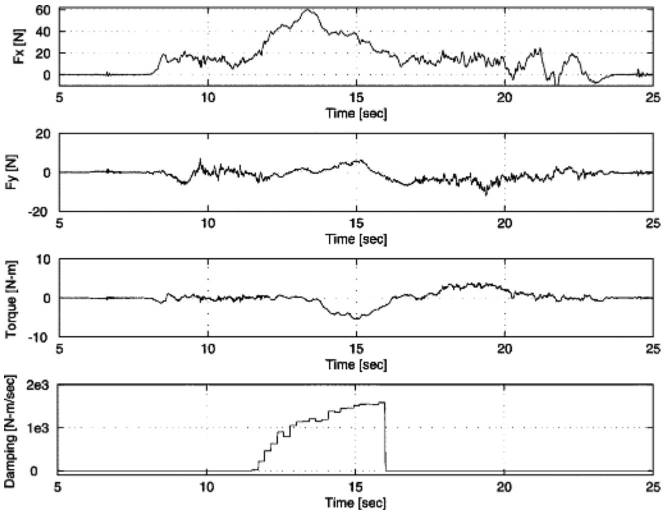


Fig. 14. Evaluation of environment feedback with passive behavior.

support system is near the environment element, the motion characteristics are changed, and this prevents the support system to go near the environment element. In Fig. 12(c) and (d), the user tries to apply an intention to move the system forward, but at this instance, the system is very heavy. This prevents any motion toward the direction of the environment element.

In the actual evaluation of the general motion control algorithm and environment feedback with passive behavior, a user is asked to navigate in an environment shown in Fig. 14. A chair is placed in the navigating path of the user. Fig. 13 shows the applied force/torque of the user and the damping along X-axis. As the system detects the environment element in region 3, D_{env_x} is increased. This makes the system heavy along X-axis. Based on Fig. 13, the applied force along X-axis increases ($t = 10$–13 s). This means that the user tries to apply more force. The environment element creates a feedback to the user, which alters the user's intention. As a result, the user tries to apply torque to steer away from the environment element.

VII. Conclusion

This paper presented a control approach based on passive behavior to enhance user interaction. This was implemented on an active (motorized) robotic walking support system. An imposed apparent dynamics that describes a passive system was used to realize the passive behavior, and it used the user's intention to derive system's desired motion. Passive behavior allows the user to interact with the support system safely since the system does not have the capability to move without user's intention.

The control approach was extended to a user-oriented motion control algorithm in adapting user's controlling characteristics, and this was implemented by varying the point of application of the apparent dynamics. In addition, the control approach also had the capability to use environment feedback by varying the parameters of the apparent dynamics based on environment information. This allows the user to change his applied intention in order to avoid some danger during navigation. Experimental results show the validity of the proposed control approach.

The future work will consider the development of some high-level functions that will further improve the user's safety during navigation. In addition, the evaluation of the support system in some elderly care facility is considered.

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