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Environment Feedback for Robotic Walking Support System Control

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Abstract— **This paper proposes a control approach for an active robotic walking support system based on environment feedback. The support system is controlled using imposed apparent dynamics and its parameters are varied by the environment information. The environment information will not cause any motion but will only change the characteristics or maneuverability of the support system. This approach leads to a passive behavior for an active walking support system. In addition, the stability of the support system based on the apparent dynamics is also discussed. This is important as a guideline on what parameters to vary that will not cause instability to the system. Experimental results are presented to show the validity of the control algorithm with environment feedback.**

I. INTRODUCTION

Environment feedback is important to enhance the interaction between human and robots. It is also a key element in developing intelligent systems. There are several fields in which it can be useful, and one of this is the control of a robotic walking support system. As an example, environment feedback can be employed to inform the support system user about the danger in the subsequent environment. This approach will allow the user to change his applied intentions in order to avoid the danger and it will improve user's safety during navigation. With environment feedback, a closed-loop between the environment and the support system user is created.

The implementation concept of environment feedback in this study is to include the environment information in the motion control algorithm of the walking support system. It will be of great interest if the support system can sense its environment and change its characteristics to improve user's safety. The unique idea that will be 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 intention, which is represented by applied force/torque, the system will not move.

This paper is organized as follows: Section II will discuss related studies on environment feedback and we will examine different types of implementation. Section III will discuss the motion control algorithm based on environment feedback which yields passive behavior. Section IV will discuss the stability issues of the motion control algorithm based on imposed apparent dynamics. This is followed by the evaluation of the proposed control algorithm, which is based on environment feedback. This paper concludes with a brief summary and a discussion on the future works of the study.

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II. RELATED WORKS

There are several studies on passive(non-motorized) support system[1][2][3] and some are employing environment feedback. In this study, we will address one basic problem on how environment feedback can be implemented in an active(motorized) robotic walking support system and we will focus on environment element that will endanger the safety of the user. In [1], a shared navigation control approach was described using a passive intelligent walker. It uses VFF(virtual force field) concept to generate force from the environment element such as obstacles. In the implementation, the force influenced the heading angle of the support system.

In [2], described a passive type of robotic walker, which uses servo brakes. This system does not have any motor for steering but it can be steered by varying the amount of brake torque in each wheel. An artificial potential field was used in [2] and a repulsive force was generated from the environment elements. The generated force was fed to the motion control algorithm and this affects the brake torque in each wheel.

Fig. 1(a) shows a support system with environment feedback. Based on the road slope, the support system applies gravity compensation control. This eliminates the possibility to move when the user releases the system. Fig. 1 (b) shows an implementation of step detection and avoidance. As the support system detects a stair step, the heading direction of the support system is changed such that the user will not fall. Fig. 1 (a) and (b) illustrated the use of environment feedback to improve user's safety by changing the system characteristics. The main difference of this study is the implementation of environment feedback on active (motorized) walking support system and the proposed motion control algorithm will possess a passive behavior. Below are the basic characteristics of a support system with passive behavior.

Passive behavior characteristics

- User powered - User should apply force/torque to the support system in order to move.
- Inactive without user intentions - The support system does not move if there is no intention such as applied force/torque.

Let us consider the conventional approach in implementing environment feedback. A potential field is created from the environment element and it is given in (1).

(a) (b)

Fig. 1. Illustration of environment feedback using passive walking support system "RT-Walker" [2]. (a) Gravity compensation control (b) Stair steps detection and avoidance.

$$U_{env\_rep}(\mathbf{d}) = \left\{ \begin{array}{ll} \frac{1}{2}(\frac{1}{\rho(\mathbf{d},\mathbf{d_{obs}})} - \frac{1}{\rho_o}) & \text{if} \quad \rho(\mathbf{d},\mathbf{d_{obs}}) \leq \rho_o \\ 0 & \text{if} \quad \rho(\mathbf{d},\mathbf{d_{obs}}) > \rho_o \end{array} \right\} \quad (1)$$

where $\mathbf{d}$ is the support system position, $\mathbf{d_{obs}}$ is the environment element position, and $\rho(\mathbf{d},\mathbf{d_{obs}})$ is the relative position of the support system and the environment element. Based on (1), a repulsive force $\mathbf{F_{env}}(\mathbf{d})$ is derived and this is given in (2). This force is used to change the heading direction of the system as described in [1][2].

$$\mathbf{F_{env}}(\mathbf{d}) = -\nabla U_{env\_rep}(\mathbf{d}) \quad (2)$$

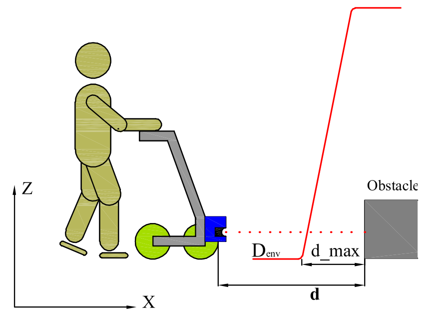
In general, the concept of potential field[7] is widely used in mobile robot navigation. Based on the aforementioned discussion[1][2], its usage is extended such that it can be applicable to robotic support system control and it excellently works for a passive(non-motorized) support system. The approach based on potential field in which repulsive/attractive forces are generated also have some disadvantages especially using a motorized robotic walking support system and we will address this in the succeeding discussions.

In this study, an active(motorized) type of robotic walking support system[4][5] is used and this is controlled using imposed apparent dynamics(desired dynamics) given in (3). $\mathbf{F_h}$ is the applied force/torque of the user. $\mathbf{M}$ and $\mathbf{D}$ are the desired inertia and damping matrices, respectively. It should be noted that (3) is the desired dynamics and from this equation, the desired velocity of the system is derived.

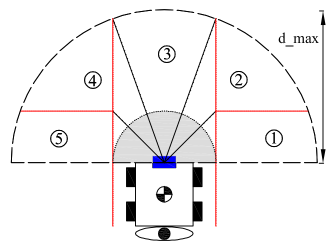
$$\mathbf{M}\ddot{\varphi} + \mathbf{D}\dot{\varphi} = \mathbf{F_h} \quad (3)$$

$\mathbf{M}$ and $\mathbf{D} \in \mathrm{R}^{3x3}$, $\mathbf{F_h} \in \mathrm{R}^{3x1}$, and $\varphi = [x \ y \ \theta]^T$. The initial conditions of (3) are assumed to be zero. Assuming we will add a repulsive force generated by the artificial potential field, the resulting motion control algorithm with environment feedback is given in (4). This equation is reasonable to cancel user's intention when an environment element is detected such as obstacle in the navigating path.

$$\mathbf{M}\ddot{\varphi} + \mathbf{D}\dot{\varphi} = \mathbf{F_h} + \mathbf{F_{env}}(\mathbf{d}) \quad (4)$$



(a)



(b)

Fig. 2. (a) Concept of variable apparent dynamics based on environment information (b) Sensor data segmentation

III. Motion Control Algorithm with Environment Feedback

In a typical operating environment of a robotic walking support system, there are several environment elements such as chairs, tables, doors, stairs, etc. These elements may affect the safety of the support system user during navigation. We will present an approach to feedback the environment information and its effect will be passive with respect to the support system. This means that the presence of environment element such as obstacles, stair steps, and others will not cause any motion to the support system. The environment information can only change the maneuverability of the support system and this is implemented by changing the parameters of the motion control algorithm.

In Section II, force is extracted from an environment element and this is augmented to the motion control algorithm. We will discuss the disadvantage of the aforementioned approach and it is a special case for an active(motorized) walking support system. Based on equation (4), 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 in different direction. In addition, when the user accidentally releases the system, this lead to $\mathbf{F_h} = \mathbf{0}$. The resulting motion equation of the support system is given in (5) and $\mathbf{F_{env}}(\mathbf{d})$ will cause some motion to the support system.

$$\mathbf{M}\ddot{\varphi} + \mathbf{D}\dot{\varphi} = \mathbf{F_{env}}(\mathbf{d}) \tag{5}$$

The aforementioned situation endangers the safety of the user since the presence of environment element, which cause a repulsive force that will make the system move without user's intention (applied force/torque). With this, we propose an approach to feedback environment information such that its effect is passive for an active(motorized) type of walking support system. The approach does not alter the intentional direction of the user but only allow the user to feel the existence of the environment element in the direction of the applied intention.

Equation (3) is modified to include environment information and to satisfy the passive effect discussed in Section II. The resulting equation is given in (6).

$$(\mathbf{M} + \mathbf{M_{env}})\ddot{\varphi} + (\mathbf{D} + \mathbf{D_{env}})\dot{\varphi} = \mathbf{F_h} \tag{6}$$

$\mathbf{M_{env}}$ and $\mathbf{D_{env}} \in \mathrm{R}^{3x3}$ and these are the inertia and damping matrices caused by the environment information. The matrices are both positive semidefinite. $\mathbf{M_{env}}$ is derived based on $\mathbf{D_{env}}$ to maintain the system bandwidth.

Fig. 2 (a) shows a damping parameter of the apparent dynamics when the support system is near to an environment element such as an obstacle. Based on (6), the parameters are designed such that they have positive values and they do not cancel the base parameters ($\mathbf{M}$ and $\mathbf{D}$).

There is a need to segment the sensor region such that a certain region can only affect certain direction. Fig. 2 (b) shows the segmented sensor region $\mathbf{SR} = \{SR_1, SR_2, .., SR_5\}$ and each region will affect different damping parameters. As an example, SR_3 will affect D_{env_x}, SR_1 and SR_5 will affect D_{env_y}, and SR_2 and SR_4 will affect D_{env_θ}. Below defines D_{env_x},

$$D_{env_x} = \begin{cases} \xi_x(\frac{d_{max_x} - d_x}{d_{max_x}}) & \text{Region 3} \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

D_{env_y} is given as,

$$D_{env_y} = \begin{cases} \xi_y(\frac{d_{max_y} - d_y}{d_{max_y}}) & \text{if Region 1 and } F_y < 0 \\ \xi_y(\frac{d_{max_y} - d_y}{d_{max_y}}) & \text{if Region 5 and } F_y > 0 \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

For an environment element affecting the steering of the support system, it should be in Region 2 and Region 4. The parameter design of D_{env_θ} should consider the distance and the angle of the environment element with respect to the support system. D_{env_θ} is given as,

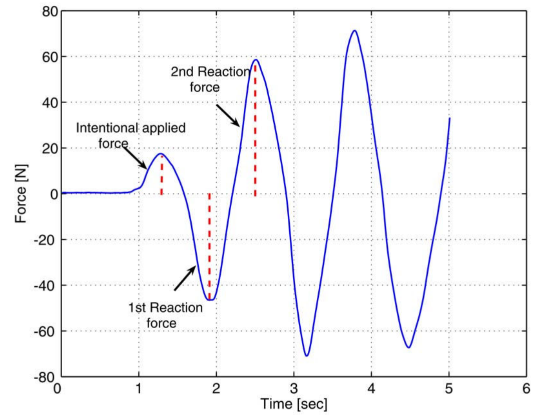


Fig. 3. Oscillations due to the reaction forces

$$D_{env_\theta} = \begin{cases} \xi_\theta((\frac{d_{max_\theta} - d_\theta}{d_{max_\theta}}) + (\frac{\theta_{max} - |\theta|}{\theta_{max}})) \\ \qquad \text{if Region 2 and } N_z < 0 \\ \xi_\theta((\frac{d_{max_\theta} - d_\theta}{d_{max_\theta}}) + (\frac{\theta_{max} - |\theta|}{\theta_{max}})) \\ \qquad \text{if Region 5 and } N_z > 0 \\ 0 \qquad \text{otherwise} \end{cases} \tag{9}$$

It should be noted that the steady state velocity of the apparent dynamics is given by $(\mathbf{D} + \mathbf{D_{env}})^{-1}\mathbf{F_h}$. This means that increasing $\mathbf{D_{env}}$ will increase the required force to maintain the user desired velocity. The increase in required applied force is the key to environment feedback. The user will feel resistance in the existence of environment element that endangers his safety.

IV. Apparent dynamics parameter guideline

The environment feedback is implemented by varying the parameters of the apparent dynamics. It is very important that the parameters that are varied will not cause instability to the support system. In [8], discussed that there are values of the apparent dynamics which leads the system into oscillations. This is illustrated in Fig. 3.

The oscillation normally happens when the user applied an intentional force to the system and come into the point that the arms are fully extended. This situation causes a reaction force, which is opposite to the intentional force. The reaction force makes the system move backward and when the system is near to the user, again a reaction force is experienced that moves the system forward. Based on the above discussion, an oscillation occurs and the reaction force expands in time. This situation endangers the safety of the user and it implies that a parameter guideline is needed to ensure the stability of the system.

Meer et. al [9] discussed the stability of flexible-object impedance controller when coupled to an arbitrary passive environment. Some guidelines were developed to ensure coupled-system stability. It is important that based on the selected parameters the system is stable.

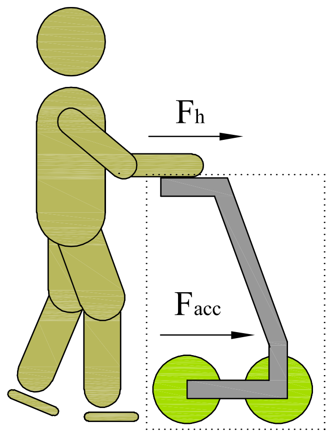


Fig. 4. Support system diagram with user applied force and actuator force

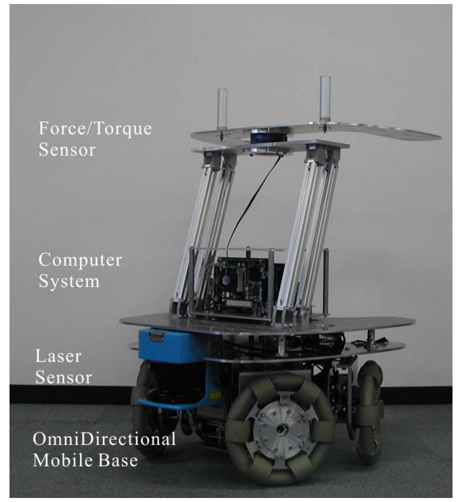


Fig. 5. Robotic walking support system : experimental platform

Let us consider a one dimension control of the support system as shown in Fig. 4 and its motion control algorithm is given by

$$M_d\ddot{x} + D_d\dot{x} = F_h \tag{10}$$

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

Assuming the actual motion equation is given by

$$M_a\ddot{x} = F_h + F_{acc} \tag{11}$$

$\mathrm{M_a}$ is the actual mass. $\mathrm{F_h}$ and $\mathrm{F_{acc}}$ are the applied force of the user and the actuator force of the system, respectively. Based on (10), the desired acceleration of the system in laplace form is given by

$$a_x(s) = \frac{F_h(s)}{M_d + \frac{D_d}{s}} \tag{12}$$

Substituting (12) to (11) leads to the relationship between the actuator force $\mathrm{F_{acc}}$ and user applied force $\mathrm{F_h}$. It is given by

$$\frac{F_{acc}(s)}{F_h(s)} = \frac{M_a - M_d}{M_d}\left(\frac{s - \frac{D_d}{M_a - M_d}}{s + \frac{D_d}{M_d}}\right) \tag{13}$$

Equation (13) can also be written as

$$G(s) = a\frac{s-b}{s+c} \tag{14}$$

where a, b, and c are given as $a = \frac{M_a - M_d}{M_d}$, $b = \frac{D_d}{M_a - M_d}$, and $c = \frac{D_d}{M_d}$, respectively.

Equation (13) gives the actuator force based on the applied force of the user. When the arms are fully extended, a reaction force at the handle is generated. If we consider this as a negative feedback, it leads to a closed loop pole around zero, which is marginally stable. This does not explain actual situation where there are values of the desired mass in which the system is stable. If we consider the reaction force creates a positive feedback, it will show that some values of the desired mass creates instability to the system.

In [9], it was also discussed that when M_d is almost equal to the actual mass M_a, the direct effect of F_h to F_{acc} is small and this leads to a stable system. The disadvantage of increasing the desired mass M_d is the dragging effect of the system. This means that as the user wants to stop, the user can feel being drag. Dragging effect due to large desired mass is not desirable since it can lead to user's fall.

Another solution to the stability issue presented in the previous discussion is to introduce a block $G_c(s)$ with a gain K.

$$G_c(s) = K \tag{15}$$

This leads to an open loop transfer function of the system given as

$$G_c(s)G(s) = K\left(a\frac{s-b}{s+c}\right) \tag{16}$$

Based on the selected value of M_d and D_d, K is selected such that the system is stable.

V. Experiment and Result

A robotic walking support system shown in Fig. 5 is used as the experimental setup in this study. It is an active omnidirectional robotic walking support system and limited for indoor purposes. The environment information is captured by a laser range finder, which is installed in the support system. The motion control algorithm of the walking support system is described in (6), where $\mathbf{F_h}$ is the applied force/torque of the user and this is read by the force/torque sensor[10].

Equation (6) should be considered as the desired dynamics of the walking support system and from this equation, the desired velocities are derived. The derived velocities are transformed into desired wheel velocities using the inverse kinematic equation and these are fed to the low level motion controller for regulation. One limitation of the imposed apparent dynamics is that the parameters should be designed such that the desired velocities will not exceed the maximum

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

Fig. 6. Environment feedback concept for passive support system. The environment element information changes the heading angle of the support system

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

Fig. 7. Environment feedback concept for active support system. The environment element information changes the parameters of the motion control algorithm

TABLE I
WALKING SUPPORT SYSTEM SPECIFICATIONS

Mass (Kgs)	$V_{x_{max}}(m/sec)$	$V_{y_{max}}(m/sec)$	$\dot{\theta}_{max}(rad/sec)$
80	0.75	1.3	3

velocities of the system. Table I shows the system specifications of the experimental platform.

A. Environment Feedback Evaluation for Passive and Active Systems

The environment feedback for passive support system based on force generation and augmentation is shown in Fig. 6. The figure shows that as the support system goes near to an environment element, the heading angle of the support system is changed. In this study, we used the concept of environment feedback 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. 7. As the support system is near to the environment element, the motion characteristics is changed and this prevents the support system to go nearer to the environment element. In Fig. 7 (c)-(d), the user tries to apply intention to move the system forward but at this instance the system had already changed its characteristics and the user feels it is hard to push. This prevents any motion towards the environment element.

B. Environment Feedback Implementation

In the actual evaluation of environment feedback, a user is asked to navigate in an environment shown in Fig. 10. A chair is placed in the navigating path of the user, which represents an actual environment element. Fig. 9 shows the applied force/torque of the user and the damping parameter values 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 9, the applied force along X-axis increases $(\mathrm{t} = 10 \sim \mathrm{t} = 13[\mathrm{sec.}])$. This means that the user tries to apply more force. The environment element creates a feedback to the user, which makes the user alter his intention. As a result, the user tries to apply torque to steer away from the environment element. The actual evaluation is shown in Fig. 8.

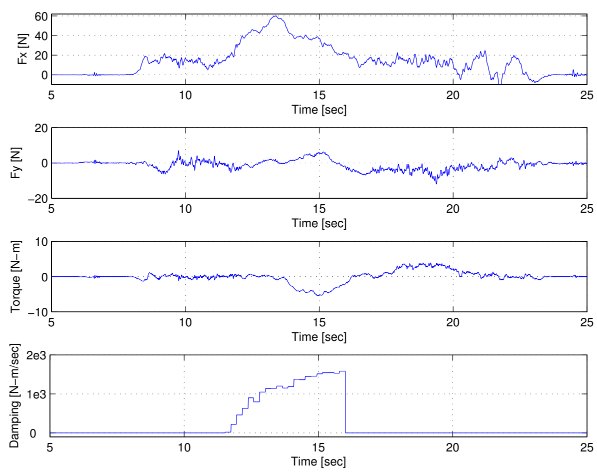


Fig. 9. User's intention represented by applied force/torque and the corresponding damping parameter due to environment element

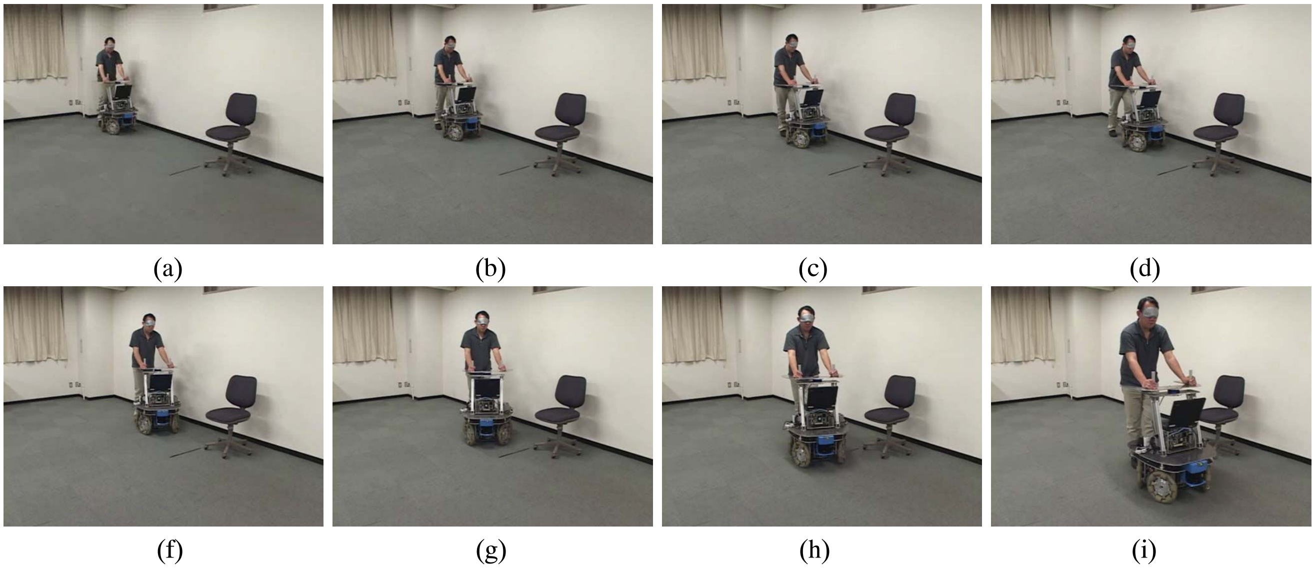


Fig. 8. Actual implementation of environment feedback.

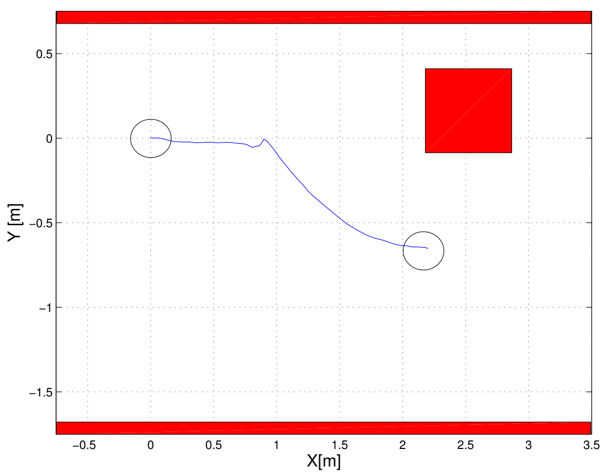


Fig. 10. Robotic walking support system trajectory during evaluation

VI. CONCLUSION

This study presented a control approach for an active(motorized) type of robotic walking support system based on environment feedback. The walking support system is controlled based on imposed apparent dynamics and its parameters were varied by the environment information. This approach yields a passive behavior to the support system since the existence of environment element that endangers the safety of the user, does not cause any motion to the support system but only changed the motion characteristics. A guideline for varying the parameters was also discussed. This is important such that the varied parameters does not cause instability to the system. Experimental results show the validity of the proposed motion control algorithm with environment feedback.

The future works of this study is focused on the development of localization module. The support system can vary its characteristics based on its pose with respect to the environment. This approach is vital to further improve the safety of the user.

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