A Navigation Algorithm using Locomotion Interface with Two 6-DOF Robotic Manipulators (ICCAS 2005)

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Abstract: This paper describes a novel navigation algorithm using a locomotion interface with two 6-DOF parallel robotic manipulators. The suggested novel navigation system can induce user's real walking and generate realistic visual feedback during navigation, using robotic manipulators. For realistic visual feedback, the virtual environment is designed with three components; 3D object modeler for buildings and terrains, scene manager and communication manager component. The walking velocity of the user is directly translated to VR actions for navigation. Finally, the functions of the RPC interface are utilized for each interaction mode. The suggested navigation system can allow a user to explore into various virtual terrains with real walking and realistic visual feedback.

Keywords: Locomotion, Navigation, Virtual Reality, Virtual Walking, Parallel Manipulator

1. INTRODUCTION

The sense of distance or orientation while walking is much better than that while riding in a vehicle for locomotion for virtual environments. Therefore, the proprioceptive feedback of walking will enhance user's immersion in most applications of virtual environments. A virtual walking machine (VWM) is an input-output device to simulate walking interactions with virtual environments without restricting human mobility in a confined space such as a room [1]. Fig. 1 shows the overall diagram for navigation with the VWM in virtual environments, which are generated by a computer. When a human walks on the VWM, the walking motions of the human are recognized by several sensors. Then, the VWM utilizes the sensed information to generate infinite surfaces for continuous walking. Also, the sensed information will be transferred to virtual environments for scene update according to motions of the human walking. Finally, a human can immerse into virtual environments by feedback of visual and locomotion information. The VWM belongs to locomotion interface that allows all mobility such as walking, running, and kneeling in virtual environments. More possible applications using locomotion interfaces are well summarized in [2].

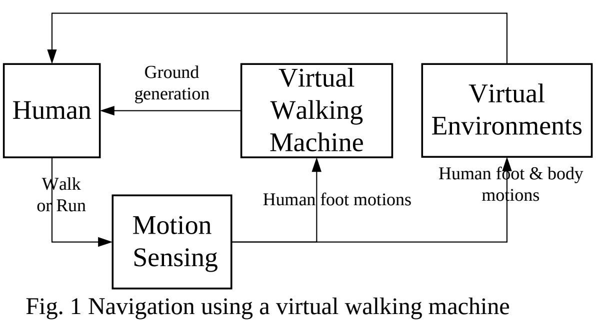


Fig. 1 Navigation using a virtual walking machine

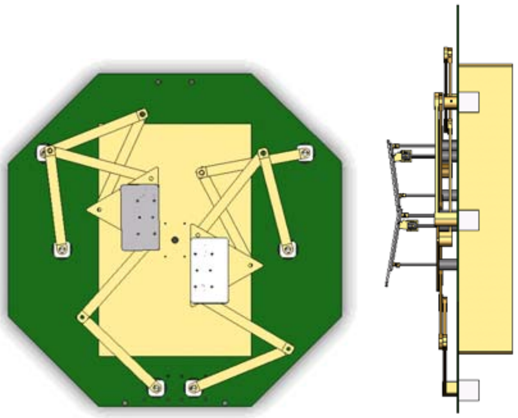
Recently, programmable foot platforms [2-5] with robotic devices are suggested to simulate even and uneven omni-directional surfaces that are required for locomotive interactions in diverse virtual environments. Even though programmable foot platform devices can ideally simulate various terrains for natural walking, there are very few experimental reports for the programmable foot prototypes with real waking except Gait Master [4]. For allowing user's continuous walking with the limited workspace of the interface, Iwata [4] suggested the principal of cancellation: while one platform will follow one foot during the swing phase, the other platform will move back the other foot. However, there are no general algorithms for navigation of locomotion interface using robotic manipulators. Therefore, it is necessary to develop a generalized navigation control algorithm that allows a user to interact with virtual environments while walking over various terrains using 6-dof programmable devices. In this paper, control and navigation algorithms that can allow continuous walking over various terrains using the proposed interface are developed.

2. LOCOMOTION INTERFACE

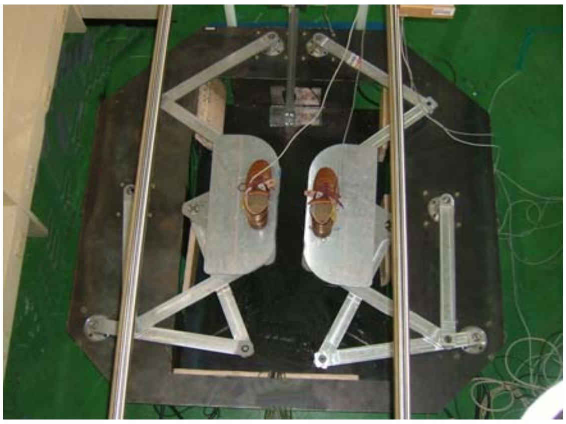
2.1 Overview

The virtual walking machine (VWM) is composed of two planar devices on which two footpad devices are mounted. The planar device [6] is planar parallel manipulator that is composed of a platform and three limbs, each of which has three serial revolute joints (RRR) with the actuated first joint. Since the actuators can be fixed on the base, the weight of moving part can be reduced. In addition, revolute joints have no mechanical limits, which significantly maximizes the workspace. The 3-dof footpad device [7-8] is composed of platform, and two limbs. One limb with 6-dof serial joints (P-S-P-P) is attached to the platform and are perpendicular to base plate, while the other limb is composed of 4-dof serial joints (P-R-R-R). The 2- dof driving mechanism at the limb with two base-fixed prismatic actuators can generate heave and roll motions. Therefore, the footpad device can generate pitch, roll, and heave motions at the platform.

Fig. 2 shows the structure of the proposed locomotion interface which is based on thorough understanding of the human gait. Ball casters are inserted between the planar device and the large base plate to significantly reduce the friction between the planar device supporting human weight and the base plate. Therefore, the planar device can generate fast and high rigidity motions with relatively small motors, while the footpad device can support continuous human weight with pneumatic actuators. The major characteristics of the proposed VWM can be summarized as follows: Separate mechanisms for planar (x, y, and yaw) and spatial (z, pitch, roll) motions; Workspace wide enough for natural human walking and force capability sufficient to support the user's weight; Presentation of uneven, omni-directional surfaces;



(a) front view (b) side view



(c) fabricated device

Fig. 2 The locomotion Interface (planar device + 3-dof footpad device)

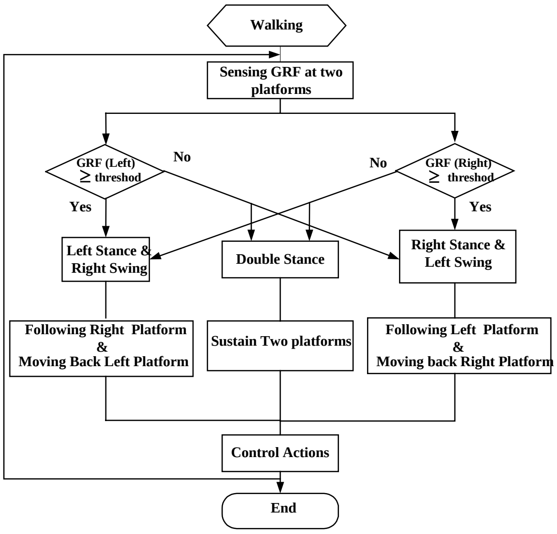
3.WALKING CONTROL ALGORITHM

The locomotion interface control system should enable a user to walk smoothly and continuously in a confined area. Thus, the control algorithm should be designed to keep the position of the human at a neutral position during walking.

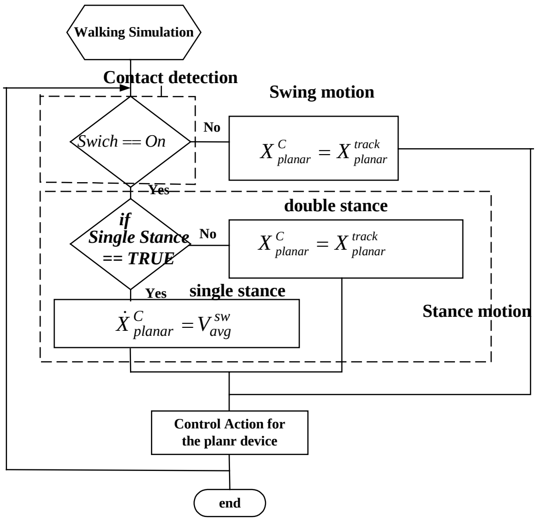
3.1 New Cancellation Method

For a single normal gait cycle, the stance phase accounts for approximately 60 percent, while the swing phase accounts for approximately 40 percent. It should be noted however that a double support phase exists during which both limbs are in contact with the ground. During this phase, the body's center of gravity is at its lowest position. These double supports happen during initial 10% and final 10% of stance phase. Therefore, we suggest new cancellations method, in which the walking motions consider double stance phase. Thus, each platform will follow the magnetic tracker attached to a foot during swing phase when human foot is moving forward without contacting any object, while the other platform will move back during single stance phase when only one foot is in contact with ground. If two feet are in contact with the platforms, the two platforms will keep their current positions. The transitions between swing and stance phase are detected by using switch sensor system exerted by the human foot.

Fig 3 (a) shows the block diagram of the proposed cancellation method. The proposed cancellation algorithm can allow a user to stop and start naturally according to user's intentions because of the added double support phases. Therefore, this algorithm will allow more natural walking on any programmable locomotion interfaces, satisfying normal gait conditions.



(a) New cancellation method



(b) Control action for each platform

Fig. 3 Walking control algorithm

The walking control algorithm for implementing this cancellation scenario on the level ground is shown in Fig. 3(b). Fig. 3(b) shows in detail that if the switch sensor is 5V, the gait cycle is recognized as swing phase and the planar motion X^{track}_{planar} of the foot tracker is inserted to the command input for motion control of the planar device. On the other hand, if the switch sensor is 0V, the gait cycle is recognized as the stance phase and the planar device moves back. In order to put back the limb in the original position with human walking speed, the average velocity V_{avg}^{sw} of a foot during the swing phase is calculated as

$$V_{avg}^{sw} = \frac{1}{T_{sw}} \int_{t}^{t+T_{sw}} X_{planar}^{sw}\, dt \qquad (1)$$

where X_{planar}^{sw} and T_{sw} are respectively the forward moving distance during the swing phase and the required time for x, y, and yaw directions. The duration T_{sw} of the swing phase will be achieved by checking the phase detection method. Then, the average velocity V_{avg}^{sw} is inserted into the control action command X_{planar}^{C} of the planar device for a single limb stance as

For single limb stance:

$$\text{If } St\_Phase == TRUE,\quad \dot{X}_{planar}^{C} = V_{avg}^{sw}$$

$$\text{If } St\_Phase == FALSE,\quad \dot{X}_{planar}^{C} = \dot{X}_{planar}^{track} \qquad (2)$$

During the double limb stance phase, the current tracker positions are inserted into control command of each platform since each limb will sustain current positions. Therefore, the control action command for each platform during the double limb stance is as

For double limb stance:

$$\dot{X}_{planar,i}^{C} = \dot{X}_{planar,i}^{track},\quad i = (L, R) \qquad (3)$$

3.2 Compensation for Neutral Positioning

The proposed walking control algorithm is basically designed for natural walking with constant speed. If a human walks with the same velocity and the platform follows the human foot without errors, the proposed walking control algorithm is basically working well. However, if there is a velocity change, a human foot may be in the swing phase before or after the backward movement to the same positions with average velocities of previous swing phase during single stance phase. This means that if a user changes his/her current velocity of walking, the backward movement during stance phase cannot reach home positions because it is calculated based on previous waking velocities of the swing phase. Due to this reason, home positioning errors generated by velocity change are inevitable. Therefore, in order to compensate home positioning error during swing and single stance phases, the control action during the double limb stance of equation (3) is changed into equation (4) as

For double limb stance:

$$\text{If } (X_{planar,R}^{m} + X_{planar,L}^{m})/2 > 0$$

$$\dot{X}_{planar,i}^{C} = -(V_{avg,R}^{sw} + V_{avg,L}^{sw})/2 \times K_{neutral},\quad i = (L, R)$$

$$\text{If } (X_{planar,R}^{m} + X_{planar,L}^{m})/2 < 0$$

$$\dot{X}_{planar,i}^{C} = (V_{avg,R}^{sw} + V_{avg,L}^{sw})/2 \times K_{neutral},\quad i = (L, R) \qquad (4)$$

where X_{planar}^{m} is the measured posture of the platform and the $K_{neutral}$ is the gain of the neutral home positioning velocities. The velocity gain $K_{neutral}$ will be determined based on the user studies. The larger gain implies the precise home positioning with the excessive inertia feeling during the backward movement and the smaller gain implies the larger home positing errors with smaller inertia feeling. Equation (4) implies that by calculating the current average positions of two platforms when the double stance phase is starting, control commands for keeping neutral positions of two platforms are determined. If average positions of the current platforms are positive, the negative velocity control action commands are applied to each platform with proportional to average velocities during two platform’s single phases. This algorithm moves center positions of the two platforms to home positions without changing the relative positions between the two platforms. Therefore, the neutral positions can be maintained although a user changes walking velocities. Consequently, the user can walk continuously on a programmable locomotion interface according to his/her intensions.

3.3 Spatial motions

For spatial motions of the locomotion interface, the footpad device will be used to generate various terrains such as stairs and slopes. In order to simulate stairs, the platform of the footpad device should have zero angles since the stairs have no slope. Therefore, cancellation method about planar motions can also be applied to lift motion control.

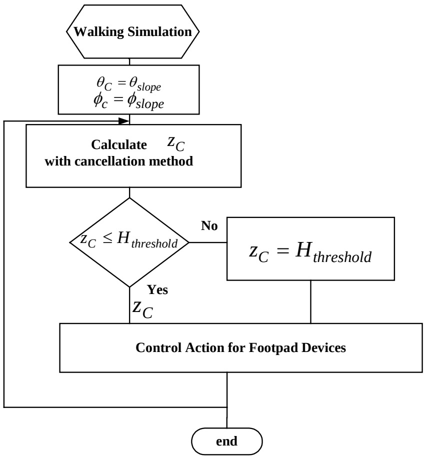


Fig. 4. Walking control algorithm for spatial motions

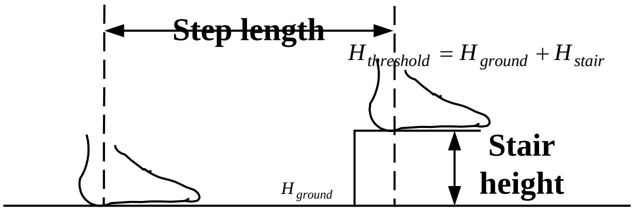
Therefore, the command input z_C of the z coordinate of the footpad device should be calculated by equations (1-4). If the z_C is higher than the ground height $H_{threshold}$, the command lift motion z_C of the footpad device will be $H_{threshold}$ to keep stairs surface. This algorithm for spatial motions is shown in Fig. 4. Planar motions at the stairs simulation can be controlled in the same way as that of the level ground walking simulation. In summary, the stairs surface should have following parameters as shown in Fig. 5(a).

$$\phi_{slope} = 0,\quad \theta_{slope} = 0,\quad H_{threshold} = H_{ground} + H_{stair} \qquad (5)$$

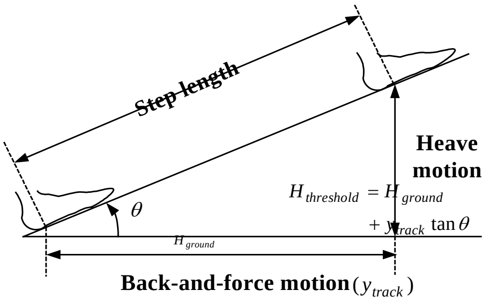
where θ_{slope} and ϕ_{slope} are the pitch and roll angle of the slope on the ground, H_{ground} and H_{stair} are the height of ground and stairs. For slope surface generation, if the pitch angles of the footpad device have constant values and the roll angle is zero, the surface will be uphill or downhill slopes. Conversely, if the pitch angle of the footpad device is zero and the roll angles have constant value, the surface will be side slopes. If ground has up-slope, the pitch angle should be positive and the ground height should be increased as human foot proceeds in forward direction as shown in Fig. 5(b). Therefore, to sustain the contact of the human foot with the ground at slope surfaces, the ground height threshold $H_{thereshold}$ should be computed in equation (6), while the same walking scheme for planar motions and lift motions will be applied to retreat the human foot back for continuous walking.

$$\theta_C = \theta_{slope} \ , \quad \phi_C = \phi_{slope} \ , \quad H_{threshold} = H_{ground} + y_C \tan(\theta) \quad (6)$$

where θ_C and ϕ_C are the desired pitch and roll angles of the footpad device, and y_C is the back-and-forth desired control command of a human foot calculated from equations (1)-(4). This walking control algorithm, therefore, will sustain continuous walking over various terrains with the 6-dof locomotion interface in a limited area.



(a) Stair



(b)Slope

Fig. 5 The walking surface generation

4. NAVIGATION USING THE LOCOMOTION INTERFACE

4.1 Virtual Environments

Virtual terrains (see Fig. 6) have been developed by using OpenGL API (Application Program Interface) based on Microsoft Visual C++ programs for window environment. The viewpoint is selected as the first person viewpoint so that operator may see virtual environment and feel more realistic. Virtual environments are displayed with large screen to guarantee safety of the subject during the locomotion interactions. Even though HMD (Head Mounted Display) can provide full sight of virtual environment, the wearing of the HMD may prevent the user from coping with dangerous situations during walking interactions on the locomotion interface. After enhancing the control performances and the safety of the VWM, the final goal is to let user wear the HMD for full immersion in the virtual navigation for real walking.

The virtual environment consists of three components:3D object modeler for buildings and terrains, scene manager and communication manager component. The 3D object modeler component provides geometric modeling functionality for virtual environment through polygon extrusion of 2D profile in the 2D map and 3D CAD model. The 2D representation of a geo-feature in the 2D map is given by a two-tuple $M^{2D} = (G, P)$, where G is a set of geometries and P is a set of non-spatial data (properties) for the geo-features. The 3D representation of the objects for virtual environment is given by a four-tuple $M^{3D} = (G, P, b, h)$, where b is a value of height from the ground and h is a value of an object's height (e.g., height of a building). The G and P are the same as the 2D representation. Therefore, the 3D model can be created for 2D map by extruding 2D profile geometry with b and m. In simple features specification of the Open GIS Consortium (OGC)[9] , the Well-Known Binary (WKB) representation for geometry provides a portable representation of a geometry value as a contiguous stream of bytes. Also, WKB representation is used to store geometry information as in OGC simple features specification.

(a) Upright navigation

(b) Slope navigation

Fig. 6 Virtual terrains

The scene manager component manages the scene graph for real-time rendering according to the VWM requests. The communication manager component manages the communication between virtual walking machine and virtual environment via remote procedure call (RPC) to interact the VWM user. The interface using the interface definition language (IDL) for RPC is defined to communicate between the VWM and virtual environment. The proposed RPC interface provides virtual environment switching and interaction functions.

4.2 Interaction between the LI and virtual environments

There are two types of RPC methods for interaction: position-based interaction and action-based interaction. The *position-based interaction* performs the navigation in virtual environments according to the position changes in local coordinate system of the VWM, while the action-based interaction performs relative motion at current virtual environments according to the velocity changes of the VWM. Since there are many virtual environments with various terrains, the *action-based interaction* is easy to control the virtual environments in that it performs the navigation according to the VWM user actions rather than the position changes. Therefore, the walking velocity of the user will be directly translated to VR actions for navigation. The update rate for the VWM velocity is selected to be 20Hz, which is enough to show smooth walking actions. Then, the user walking velocity is estimated as;

Single Right Stance Phase:

$$V_{walking} = V_{avg,L}^{sw} \tag{7}$$

Single Left Stance Phase:

$$V_{walking} = V_{avg,R}^{sw} \tag{8}$$

Double Stance Phase:

$$V_{walking} = 0 \tag{9}$$

where the $V_{walking}$ is the estimated walking velocity of a user on the locomotion interface. Since human foot moves forward only during swing phase, the average velocity of the human walking can be estimated as average velocity during only swing phase motion. Therefore, after the each foot moves forward and when the foot contacts on the platform, the walking velocity will be updated. During double limb stance, since the foot will not move forward, the velocity should be set to zero. Finally, the functions of the RPC interface shown in Fig.7 are utilized for each interaction mode.

```
// switch various virtual environments such as floor, sloop,
turning and stairway.
void SetEnvMode (int mode);

// control position-based interaction.
void SetVWMParam (VWMPosition point,
VWMOrientation orientation);
void SetVWMCameraParams (VWMPosition focal,
VWMPosition point, VWMOrientation orientation);

// control action-based interaction.
void Forward (float speed);
void Backward (float speed);
void LookLeft (float angle);
void LookRight (float angle);
void LookUp (float angle);
void LookDown (float angle);
void UpStair (float speed, float ratio);
void DownStair (float speed, float ratio);
```

Fig. 7 RPC interface for interaction between the VWM and virtual environments.

The functions ***Forward*** *(speed)* and ***Backward*** *(speed)* for back-and forth motions will move the current camera position to the next camera position towards the direction vector of the current camera. The *speed* will determine differential displacement during sampling time. Similarly, the functions ***UpStair****(speed)* and ***DownStair****(speed)* will change the camera position of virtual environments for z direction. The functions ***LookLeft*** *(angle),* ***LookRight*** *(angle),* ***LookUp*** *(angle),*and ***LookDown*** *(angle)* are defined to change directions of the camera, which will be connected to HMD(Head Mounted Display) to reflect the change in user's view in virtual environments.

4.3 Evaluations

For the preliminary interface evaluation, five subjects among our laboratory students participated in walking over the designed locomotion interface device. The subjects who have no experience of the walking on the interface were instructed how to walk over the walking interface. Since there is velocity limitation (maximum 1.2m/s) for the locomotion interface, they were requested to walk with normal speeds that they generally walk. Even though the number of subjects is small, it is useful for discussing the overall performance of the walking interface. Initially, most of them were afraid of the waking on the interface but after trial walking, they were able to walk without anxiety. Fig. 8 shows the scores of the each item (safety, reality, and overall) for upright walking with respect to subjects A…E. After interactions with the walking device, they scored each item. It was observed that the tracking performance of the locomotion interface was dependent on the height and weight of the subject. In the case of the subject lesser than 180cm, their walking motion was not disturbed due to the large workspace of the walking interface. However, in the case of the subject higher than 180cm, sometimes, the controller of the VWM was failed to follow the subject walking due to the excessive torques. The total weight of the one platform part of the VWM that include the platforms of the planar and footpad device, the ball casters, and pneumatic cylinders is over 30kg. This large inertia prevents the VWM from moving with faster speed than 1.2m/s. Most of them are satisfied with the walking control algorithm since the algorithm has been developed based on the real human gait motions. But, they indicated that for moving back motions during stance phase, they felt the body inertia of moving back motions due to the neutral home positioning during double stance phase. For overall evaluations, subjects generally were satisfied with the reality of the walking with the interface device. However, even though none of the participants suffered from any dangerous situation during the evaluation test, they indicated that the noises of the ball casters become severe as the walking speed increases. For stairs and slope walking on the interface shown in Fig. 9, the subjects were more positive for real walking in that there was not much of the body inertia for backward motions, especially for the back-and-forth motions. Since real bodies were moving up and moving down for walking interaction on stairs and slope grounds, they felt that their walking motions were more similar to real walking. Even though there were small vibrations of the footpad platform, the subjects were not so sensitive to feel the unnaturalness. For safety, they can maintain their balance compared with the upright motions that had large back-and-forth motion. But, during fast lift motions, the pneumatic actuators suffered from the small source of the air supply since the six pneumatic actuators with the diameter of 50 cm were operating simultaneously. Consequently, the pneumatic system becomes unstable. For turning motions shown in Fig. 10, most of the subjects were not satisfied with the naturalness since their turning motions were severely limited due to the collisions between left and right platforms. In addition, since the yaw motions of the each foot during swing phase continuously changes during normal gait, the yaw motions of the platforms also changes during swing phase without intention of the turning motions. Moreover, the magnetic tracker itself for yaw directions had higher level of noise, which generated vibrations of the platform during tracking. Consequently, the turning motions were not realistic. For thorough evaluations of the proposed locomotion interface, the gait analyses will be performed for different types of ground surfaces.

With preliminary evaluations, some important understandings of the developed locomotion interface are addressed. The walking control and navigation algorithm was operating well with the proposed novel programmable locomotion interface. The walking interactions with the upright, stairs, and slope grounds were successful on the locomotion interface. There were limitations such as speed limit, small oscillations at the instant the foot contacts the platform, and noises from ball casters, valves' operations during intake and exhaust of the air, and motor cogging torques. However, the proposed novel interface provided a possibility for the patient to perform natural walking with full immersion and realism over various grounds such as upright, stairs, slope with single device.

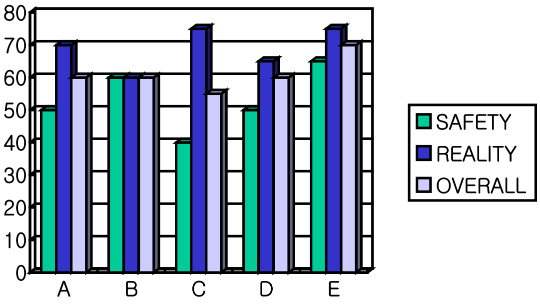


Fig. 8 Evaluation results for upright walking

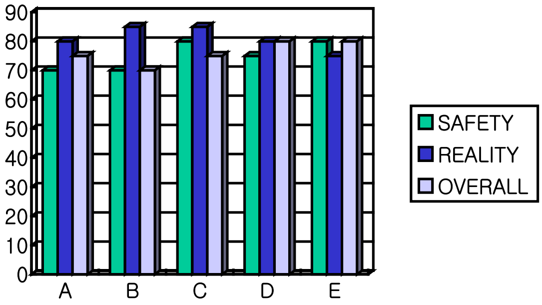


Fig. 9 Evaluation results for stairs and slope walking

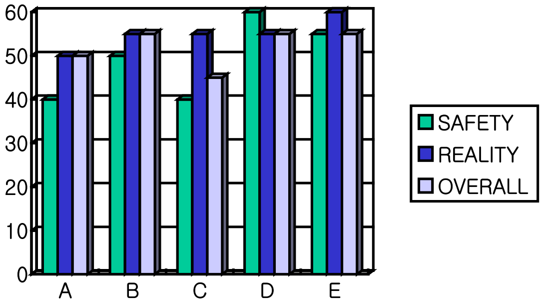


Fig. 10 Evaluation results for turning walking

5. CONCLUSIONS AND FUTURE WORK

This paper proposes novel navigation system that can induce user's real walking and generate realistic visual feedback during navigation, using robotic manipulators. For realistic visual feedback, the virtual environment is designed with three components; 3D object modeler for buildings and terrains, scene manager and communication manager component. The suggested navigation system can allow a user to explore into various virtual terrains with real walking and realistic visual feedback. As future works, the various haptic effects such as soft and hard grounds, or slippage will be simulated by changing the impedance parameters. After enhancing the control performances and the safety of the VWM, the final goal is to let user wear the HMD for full immersion in the virtual navigation with natural walking.

ACKNOWLEDGMENTS

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REFERENCES

[1] J. Yoon, J. Ryu, and G. Burdea, "Design and Analysis of a Novel Virtual Walking Machine," *IEEE 11th Haptic Symposium (in conjunction with IEEE VR conference)*, pp. 374-381, LA, CA, March 22-23, 2003.

[2] J. M. Hollerbach, "Locomotion interfaces," in: *Handbook of Virtual Environments Technology*, K.M. Stanney, ed., Lawrence Erlbaum Associates, Inc., 2002, pp. 239-254.

[3] G. P. Roston and T. Peurach, "A Whole Body Kinesthetic Display Device for Virtual Reality Applications," *Proc. of IEEE Int'l Conf. on Robotics and Automation*, pp. 3006-3011, 1997.

[4] H. Iwata, "The GaitMaster: Locomotion Interface for Uneven Virtual Surface," *Proc. of 4th VRSJ Annual Conf.*, pp. 345-348, 1999.

[5] H.Schmidt, D. Sorowka, S. Hesse, & R. Bernhardt, "Design of a Robotic Walking Simulator for Neurological Rehabilitation," *IEEE/RSJ Int. Conf. On Intelligent Robots and Systems*, pp. 1487-1492, 2002.

[6] J. Yoon and J. Ryu, "The Development of the 3-DOF Planar Parallel Robot (RRR Type) for Omni-directional Locomotion Interface", *3rd IFAC Symposium on Mechatronic Systems*, Sept.6-8, Sydney, Australia, 2004.

[7] Yoon, J. and Ryu, J. "A New Family of 4- Dof Hybrid Parallel Mechanisms with Two Platforms and Its Application to a Footpad Device," *Journal of Robotic Systems*, Vol. 22, No. 5, pp. , 2005

[8] Yoon, J., Ryu, J. and K. Lim, "Development of a Novel Reconfigurable Ankle Rehabilitation Robot for Various Exercise Modes," *Journal of Robotic Systems*, **in review**, 2005.

[9] Open GIS Consortium, *OpenGIS Simple Feature Specification for OLE/COM*, OpenGIS Implementation Specifications, Revision 1.1, 1999.