

Design and Walking Algorithm of a Foot-Pad Omni-directional Locomotion Interface

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Abstract. This paper proposes a novel foot-pad omni-directional locomotion interface, establishes planar walking algorithm for it in detail. The proposed locomotion interface allows users walking omni-directionally in a virtual environment, which can improve users' immersion characteristic significantly. The established walking algorithm explains the relation between the motion of foot-pads and the position of ankles, during walking straight or turning. At last, draw a criteria which can be used to decide walking straight or turning.

Introduction

Locomotion interface (LI) has been widely used in immersive virtual reality system. LI creates a sense of walking in a virtual environment (VE), without damaging the sense of distance and orientation during walking, while a user's true position is maintained in the real word [1].

The main existing locomotion devices can be classified into four types [2]: foot-pad, robotic tiles, treadmills, sliders. Foot-pad is one of the best approaches to create sense of walking on uneven surface. University of Utah developed a foot-pad LI, named BiPort [3], with two large manipulators driven by hydraulic actuators, which is too expensive to be applied. Rosten [4] developed a similar device "Whole Body Display" at the Cybernet Systems Corporation, which is too large to be located inside a laboratory. Iwata [5] developed "Gait Master" which consists of two 6-DOF platforms mounted on a turntable. While the available stride distance is too small to allow normal walking and the user's feet are attached to platform by straps, which limit both feet motion. Schmidt [6] developed a new solution "Haptic Walker" comprising two programmable foot platforms with permanent foot-machine contact, which limits the relative turn motion between feet and platforms. Yoon [7] [8] [9] developed a Virtual Walking Machine which consists of two 4-DOF platforms mounted on a 3-DOF parallel manipulator turntable and proposed a symmetric walking cancellation algorithm and planar curved path walking algorithm. However details to control the motion of foot-pads are not shown.

This paper presents the design of foot-pad-based omni-directional LI and describes the planar walking algorithm including walking straight line and turning in detail.

Design of the LI

The hard core elements of the foot-pad-based omni-directional LI are two 2-DOF manipulators mounted on a turntable. The actuator of the manipulator is foot-pad that can simulate omni-directional surface on which user can walk naturally.

The LI consists of four parts as shown in Figure1 (a). Part one is a turntable which traces user's walking direction momentarily. Part two are two linear guideways. One of them is used to make one foot-pad to trace swing foot, while another is used to move user back. Part three are two auxiliary turntables which can work with the turntable to trace user's foot angles. Part four are two pads which support user just as road surface during walking.

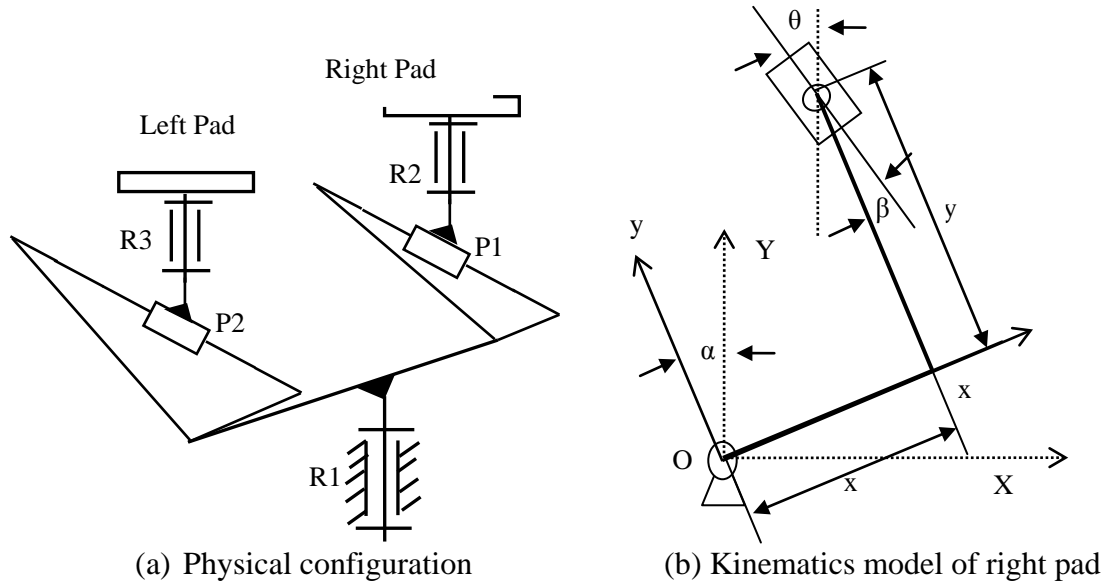


Fig.1 Design of the LI

As shown in Figure1 (b), O is the center of the LI. The current center position of foot-pad in the dynamic coordinate system is defined $P(x, y)$, while in static coordinate system is defined $P(X, Y)$. Given α is the rotation of turntable, whose radius is R_0 . y is the displacement of foot-pad on the linear guideway whose length is L_{\max} . θ is rotation of foot-pad, whose relative rotation to the turntable is β . The position and posture can be defined as:

$$\begin{bmatrix} X \\ Y \\ \theta \end{bmatrix}_i = \begin{bmatrix} \pm\sqrt{y_i^2 + x_i^2} \cos\left(\alpha + \arctan \frac{y_i}{x_i}\right) \\ \pm\sqrt{y_i^2 + x_i^2} \sin\left(\alpha + \arctan \frac{y_i}{x_i}\right) \\ \alpha \pm \beta_i \end{bmatrix} \quad (1)$$

Where $\alpha \in [0, 2\pi)$, $\beta \in [0, \pi/2]$, $y \in \left[-\frac{L_{\max}}{2}, \frac{L_{\max}}{2}\right]$, $x_R = R_0$, $x_L = -R_0$. If $i = R$, take +. If $i = L$, take-.

Walking algorithm

The motion of foot-pads must cancel the motion of the feet to keep the user's position at the center position of the LI. During swing phase, the no load foot-pad traces the swing foot, while the loaded foot-pad supports the user's body and carries user back in accordance with the displacement of the swing foot. During double stance phase, both foot-pads keep still and support user when feet rotate relative to ankle joints.

The basic function of LI is to walk straight line when the walker's walking direction is not changed. The main problem is to calculate the movement of linear guideways. Given α_0 is the previous walking direction during last swing. With Eq. (0.1) we can derive the movement of linear guideways as:

For the swing phase (single stance phase),

$$y_i = \begin{cases} -X & \alpha_0 = \frac{\pi}{2} \\ X & \alpha_0 = \frac{3\pi}{2} \\ \frac{Y}{\cos \alpha_0} - R_0 \tan \alpha_0 & \text{else} \end{cases} \quad (2)$$

$$y_L = -y_R \quad (3)$$

For double stance phase,

$$p_i(x, y, \theta) = C \quad (4)$$

Where $i=L$ or $i=R$.

When turning, two main strategies, step turn and spin turn, arise for the feet placement [10]. The trajectories during goal-oriented human locomotion in humans were recorded [11]. The trajectory during turning can be divided into two phases. Phases one is walking straight line. Phases two is walking curved path. Assuming left foot is standing on the loaded pad, and right foot is swinging. As shown in Figure2, the red lines show the trajectories of right foot, while the black lines show the left foot. And the solid lines are trajectories of walking straight line. The hidden lines are curved path of spin turn. And the dot lines are curved path of step turn.

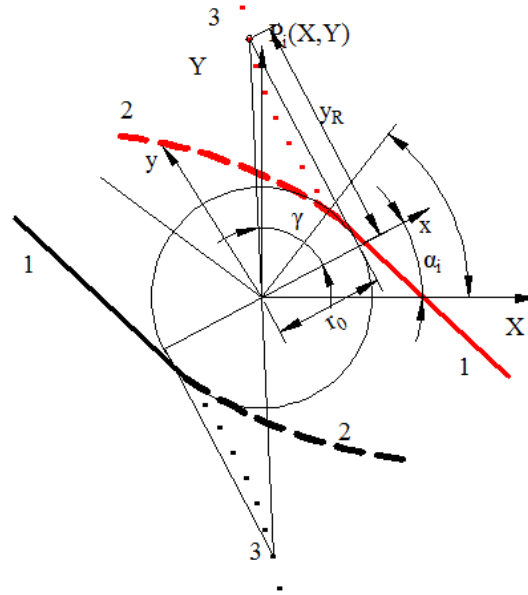


Fig. 2. Step turn and spin turn

Given α_0 is the previous walking direction during last swing and α_i is the current direction during turning.

With Eq. (0.1), we can draw a criteria what can be used to decide which phases as:

$$\delta = Y \cos \alpha_0 - X \sin \alpha_0 \quad (5)$$

Where (X, Y) is current coordinate of ankle center during swing in static coordinate system. The conclusion can be described as:

$$\begin{cases} \delta \leq 0 & \text{phase one} \\ \delta > 0 & \text{phase two} \end{cases} \quad (6)$$

In phase one, with Eq. (0.2), we can control the movement of linear guideways as:

$$y_i = \begin{cases} -|X| & \alpha_0 = \frac{\pi}{2} \quad \text{or} \quad \alpha_0 = \frac{3\pi}{2} \\ -\left| \frac{Y}{\cos \alpha_0} - R_0 \tan \alpha_0 \right| & \text{else} \end{cases} \quad (7)$$

In phases two, with Eq. (0.1) the current direction can be calculated as:

$$\alpha_i = \begin{cases} \frac{\pi}{2} - \arccos \frac{r_0}{Y} (X = 0, Y \geq 0) \\ \frac{3\pi}{2} - \arccos \frac{r_0}{-Y} (X = 0, Y \leq 0) \\ \gamma - \arccos \frac{r_0}{\sqrt{X^2 + Y^2}} (X \neq 0, Y \geq 0) \\ \pi + \gamma - \arccos \frac{r_0}{\sqrt{X^2 + Y^2}} (X \neq 0, Y \leq 0) \end{cases} \quad (8)$$

Where $\gamma = \arctan \frac{Y}{X}$, $\gamma \in [0, \pi)$. With the movement of ankle, α_i can be calculated dynamically as above. Then the rotation of auxiliary turntable can be calculated as:

$$\begin{bmatrix} \beta_R \\ \beta_L \end{bmatrix}_i = \begin{bmatrix} \phi_R - \alpha \\ \phi_L + \alpha \end{bmatrix}_i \quad (9)$$

The movement of linear guideways can be calculated as:

For swing phase,

$$y_i = \sqrt{X^2 + Y^2 - R_0^2} \quad (10)$$

$$y_L = -y_R \quad (11)$$

Where $i=L$ or $i=R$. During double stance phase, the posture of foot-pads is the same as shown in Eq. (0.4).

Actually, with Eq. (0.8) and α_0 we can draw a criteria which can be used to decide walking straight line or turning as:

For right foot swing phase,

$$\begin{cases} \alpha_i = \alpha_0 & \text{straight line} \\ \alpha_i > \alpha_0 & \text{spin turn} \\ \alpha_i < \alpha_0 & \text{step turn} \end{cases} \quad (12)$$

For left foot swing phase,

$$\begin{cases} \alpha_i = \alpha_0 & \text{straight line} \\ \alpha_i > \alpha_0 & \text{step turn} \\ \alpha_i < \alpha_0 & \text{stin turn} \end{cases} \quad (13)$$

In the step turn, the change of direction is opposite to the contact foot, which results the supporting area of user enlarges during turning. In the spin turn, the change of direction and the contact foot are the same size, which results supporting area diminishes.

Conclusions

This paper has shown our research activities on a friendlier foot-pad-based locomotion interface for planar omni-directional walking. The established walking algorithm are introduced in detail, which can be sued to control motion of foot-pads. And we have drawn a criteria to decide turning or not.

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