Walking Control of a Dual-Planar Parallel Robot for Omni-directional Locomotion Interface *

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Abstract **This paper presents walking control of a novel omni-directional locomotion interface with a dual-planar parallel robot. The suggested interface can generate infinite floor on planar surfaces, allowing user's upright and turning walking motions. To provide continuous walking in a confined area, a walking control algorithm is suggested for planar surfaces. For continuous walking, each independent platform of the locomotion interface will follow a human foot during the swing phase, while the platforms will move back during single stance phase. For accurate foot tracking control, magnetic trackers are attached on each shoe with careful calibration and transition phases between the swing and the stance phases are detected by using switch system, which is composed of light steel plate, spring, and micro switch. For double limb support, two platforms will manipulate neutral positions to compensate the offset errors generated by velocity change. This algorithm can satisfy natural walking conditions for any directions of planar surfaces. From experimental results, a subject can walk naturally for upright motions without significant limitations, while limitations of maximum yaw angle of 20° are applied to each platform to prevent the collisions of two platforms during turning motions. By using the suggested interface, it is anticipated that a user can interact with virtual normal pathways by real walking including upright and turning motions.**

Index Terms – Locomotion interface, planar parallel robot, continuous walking.

I. Introduction

Walking is the most natural way to move in everyday life. Locomotion Interface (LI) 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]. As virtual reality (VR) and robot technologies are rapidly developing, a LI may become indispensable to enhance the feeling of immersion in a VR system. LI allows users to participate in a life-like walking experience in virtual environments and to feel real spatial sense by generating appropriate ground surfaces to human feet. Especially, in order to experience the natural navigation on given virtual environments, the turning motion of the human during walking will be essential to change the walking direction and navigate various pathways. If the users are all the time facing the screen center during walking interaction with the virtual environments, the projection system for virtual environments doesn't need to provide expensive full 360deg screen. Therefore, it is important to keep the neutral position of LI, allowing the turning motions of the user as well as natural upright walking. Several different types of locomotion interfaces including turning motions have been proposed. The devices can be classified into four types: linear treadmills with turning strategies, planar treadmills, linear treadmill or programmable foot platforms with a turntable, and passive user walking with a turntable. The treadmill type locomotion interfaces have been initially utilized. The Sarcos Treadport [2] with linear treadmills allows a user to walk, run, and kneel at level ground or slopes. Using the Treadport, Hollerbach et al. [3] suggested the turning strategies: head twist strategy and the sidestep strategy. But, these turning strategies with linear treadmills cannot mimic real turning motions. In order to allow real omni-directional walking motions of the user, 2D treadmill types [4-5] have been suggested to allow the user to do turning motions. But, these interface are highly complex and have difficulties in generating fast upright motion. Wang et. al [6] suggested the powered offset caster transmission to realize the omni-directional motion. Eyre [7] proposed Spherical Projection System with a large 3.5 metre diameter translucent sphere. However, their experimental performances [6-7] with real walking have not been reported yet.

Some researcher suggested the turntable type for turning motions of LI. Noma [8-9] suggested "ATLAS", which has a treadmill platform mounted on a turntable and can turn on the platform to change the walking direction. The user's turning motions during walking were cancelled by rotating the turntable of the interface according to user's feet motion in swing phase. Bouguila et al. [10] initially developed the turntable type locomotion interface and upgraded the device [11] in order to generate tilt motion with three air cylinders mounted beneath the turntable. But, their device couldn't allow a user to do real walking on the interface since the device couldn't cancel the forward or backward moving motions as well as lateral motions.

For programmable foot platform, Iwata [12] developed the "Gait Master" which consists of two 3-dof translational (x, y, and z) Gough-Stewart Platforms and a turntable, which should support all other structures at bottom of the devices. Then, he 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, this algorithm didn't consider double limb stance, at which the two feet are

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simultaneously in contact with ground. Without considering double support phase, a user on the locomotion interface can have difficulties in starting or stopping walking. The Sarcos Biport [1] employed three-axis hydraulic serial-drive platforms for each foot. The device can simulate translational motions of the articulated arm in 3D space. However, since user's foot was attached to the platform, the device may disturb the natural walking if the force control is not operating well.

Therefore, the efficient omni-directional interfaces allowing turning and upright motions with simple structure and high performance are in the high demands for better locomotion interface design. In addition, it is necessary to suggest new cancellations method to walk smoothly and continuously in a confined area. In this paper, we propose a omni-directional interface with a dual- planar parallel robot with a turning capability and suggest a novel walking control algorithm for continuous walking in a confined area, satisfying natural walking conditions. The following section explains the system overview. Section III presents sensing system of the suggested locomotion interface. Section IV presents a control algorithm of the interface to allow continuous walking for infinite planar floors. Section V shows some experimental results of walking simulations. Conclusions and future research items are summarized in Section VI.

II. System Overview

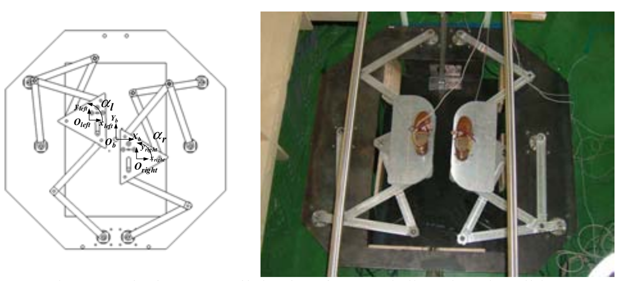


Fig.1 Dual-planar parallel robot for omni directional walking

The suggested mechanism for omni-directional walking is composed of two independent planar parallel robots. Each platform of the two planar parallel robots is composed of three limbs, each of which has three serial revolute joints with the actuated first joint. Since the actuators can be fixed on the base, the weight of the mobile equipment can be reduced. In addition, revolute joints have no mechanical limits, which significantly maximizes the workspace. To simulate natural human walking, the locomotion interface design specifications are acquired based on gait analysis and each mechanism is optimally designed and manufactured to satisfy the given requirements. The designed locomotion interface allows natural walking (step: 0.8m, foot angle: 30deg). Control and design issues of the suggested device can be found at [13].

All links of the planar device are made of light aluminum frames in order to reduce link inertia. Rotary servomotors with 3KW power (maximum torque 86Nm) are directly connected to lower bars without reduction gears. This direct drive can achieve low friction and high bandwidth and eliminate backlash and therefore the device can exhibit fast motions. This construction is possible due to the fact that all motors are fixed at the common base, which allows use of high power motors without increasing moving inertia. In addition, in order to reduce joint frictions, ball bearings are inserted at every revolute joint. Also, ball casters are inserted between the interface and the large base plate to reduce significantly the friction between the platform supporting human weight and the base plate. Therefore, the interface can generate fast and high rigidity motions. The developed locomotion interface is shown in Figure 2.

III. Sensing of Human Walking

A. Position Sensing of Human Walking

In order to follow a human foot during the swing phase, the position and orientation of the human foot are measured using Polhemus 3D magnetic trackers (FASTRACK^{TM}). The tracker-sampling rate was set to 25Hz. They are relatively inexpensive, are convenient to use, and do not suffer from the line of sight problem. A magnetic tracker is tightly attached to the shoe.

The magnetic tracker, however, generally suffers from magnetic noises caused by metals in the platforms. As the distance between a receiver and a transmitter increases, the measurement errors become severe. FASTRAK specifications say that the specified accuracy is guaranteed only when standard receivers are located within 30 cm of the standard transmitter. Therefore, careful calibration had been performed to improve the accuracy of the magnetic tracker by compensating both the position and orientation errors.

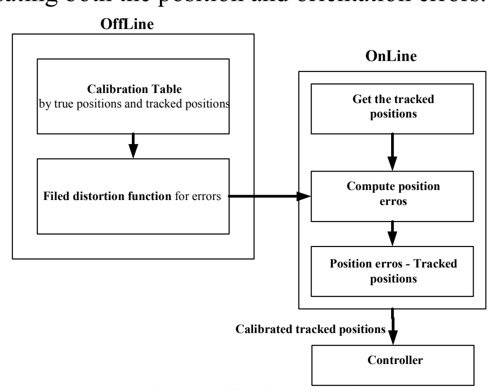


Fig. 2. Calibration procedures

To compensate measurement errors, it is necessary to experimentally obtain a calibration table that contains true positions of the tracker sensor and the corresponding tracked positions inside the allowable workspace. In order to store true and tracked position/orientation, the receiver is attached on the shoe on the platform, and is moved by the motion of the platform. The true positions are then acquired by numerically calculating forward kinematics of the platform after sensing of motor rotation angles. Then, the magnetically measured tracked positions of the receiver are stored with the true positions. Based on these measurements, a field distortion function [14] can be calculated numerically off-line. Once the function is known, it can be used to compute the position errors at any tracked location. Finally, this error can be subtracted from the tracked values so that true position is found. This procedure for calibration is shown in Fig. 2.

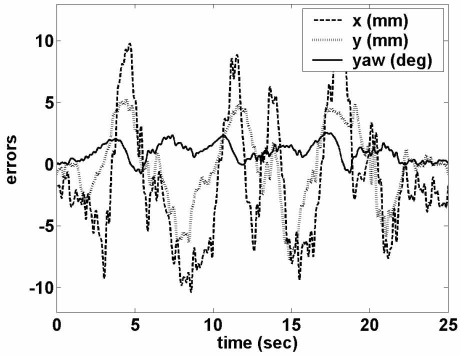


Fig. 3 Calibration results of a magnetic tracker

For experiments, the magnetic receiver attached to a shoe and the platforms were moved together in arbitrary directions by human hands. Before and after calibration, the positions and orientation from the magnetic receiver are compared with the computed positions and orientation of the platform. Fig. 3 shows the calibration results for x, y, and yaw directions (lateral, forward, turning). Significant improvements are achieved with about 600 measurements. By the calibration, accuracies are increased about three to four times, especially for y direction. After calibration, the maximum errors for x,y, yaw axis are, respectively, about 10mm, 6mm, and 3degree. Even though the accuracies in the lateral and turning directions are not perfect, a large plate of the mobile platform can cover the foot trajectories.

B. Phase Transition Detection by Switch Sensors

Micro switch sensors were suggested to guarantee simple and robust phase detection regardless of user's weight. The micro type switch sensor (Honeywell Corp., SZM-Z15-G16) is selected since it can allow mechanical speed of maximum 240 operations per minute and it can change the switch phase with small force (about 100gf). With desirable characteristics to detect normal walking phase, the switch sensors have been successfully incorporated to the platform as shown in Fig. 4. The body of the switch sensor is located below the platform, while the switch protrusion and a light steel plate are located above the platform. The light steel plate aims to transform walking actions by human foot into pushing for switch sensing. The steel plate has size of 350mm* 250mm*2mm and has curve shape to let press on any place of the plate push the protrusion of the switch sensor. The spring between the steel plate and the switch protrusion is set to keep the interval of the switch and the steel plate after push motion. The spring stiffness is selected to be enough to support steel plate. 5V and 0V are supplied to the NO and NC terminal, respectively. Then, the Com terminal is connected to Digital Input (DI) module. If human foot touches the steel plate, the protrusion of the sensor will connect the NC terminal to the NO terminal. As a result, the COM terminal will be changed to 5V from 0V. The proposed switch sensor can detect walking phase transition with small errors and short time delay.

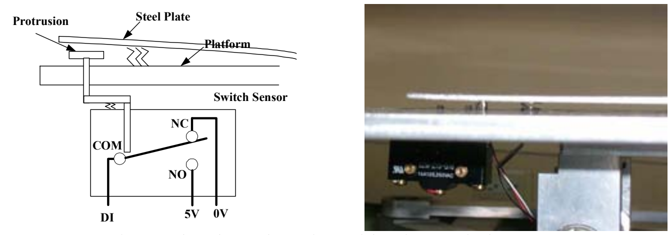


Fig. 4. The phase detection with micro switch sensor

IV. 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.

A. 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.

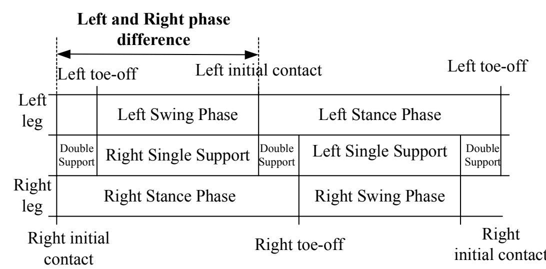
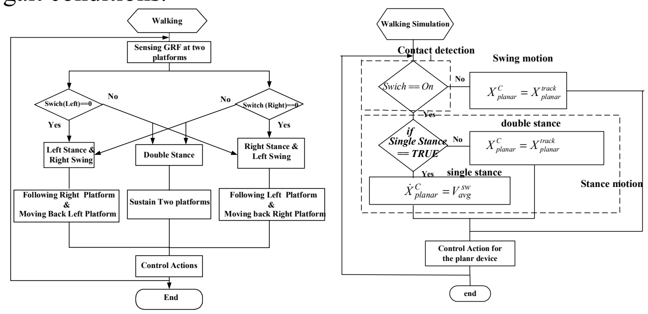


Fig. 5. Normal Gait Cycle with double support [15]

If at least one limb is in the swing phase, human is moving forward while feet are not moving forward during stance phase. In addition, since swing and single stance phase are respectively 40%, the platform during single stance phase should move back the same distance that it has moved forward during swing phase. On the other hand, two feet should not move during the double stance periods. Without considering double support phase, a user on the locomotion interface had difficulties in starting or stopping walking. 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 as explained in section 3. Fig 6 (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. 6. Walking control algorithm

The walking control algorithm for implementing this cancellation scenario on the level ground is shown in Fig. 6(b). Fig. 6(b) shows in detail that if the switch sensor is 5V, the gait cycle is recognized as swing phase and the planar motion X_{planar}^{track} 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

$$V_{avg}^{sw} = \frac{1}{T_{sw}} \int_{t}^{t+T_{sw}} \dot{X}_{planar}^{sw} dt \tag{1}$$

where $\dot{X}_{planar}^{sw}$ and T_{sw} are respectively the forward moving velocity 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:

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

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

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:

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

B. 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:

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

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

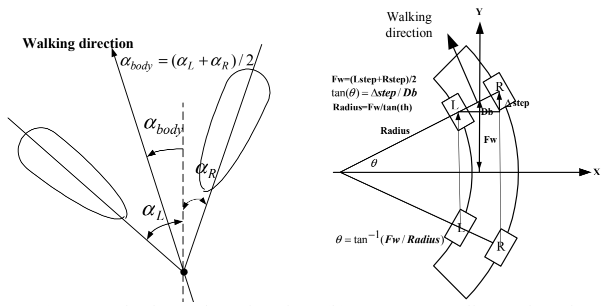
If $(X_{planar,R}^{m} + X_{planar,L}^{m})/2 < 0$,

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

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.

C. Estimation of Body Angle for Turning Walking

In order to change the current walking direction, the instant orientation of a user body at one step for turning may be estimated by averaging directions of two feet at starting point of each stance phase as shown in Fig. 7(a). For the proposed programmable foot interface with two separate footpads, turning motion of each foot movement as well as x and y motions will be cancelled by the walking control algorithm proposed in Section IV. Therefore, the platforms will rotate and follow each turning foot during swing phase, while the platform will rotate back during stance phase. The acquired instant orientation for body will be transferred into virtual environments for updating scenes. Comparing to the turntable type locomotion interfaces, the proposed locomotion interface has small turning angle to change walking directions because the two platforms may collide each other. Even though each platform can generate maximum yaw angle of 40° inside translational workspace, the maximum allowable angle was set to 20° to prevent potential collisions. Due to the limitation of the small rotation angle, the proposed interface cannot allow abrupt turning motions, which needs large rotation at one step. However, the general pedestrian ways are composed of about 2-10 m curvature radius. If one step is about 0.5m, then the required body angle become 5.7°-18.4° by using the relations as shown in Fig. 7(b).



(a) Instant body angle estimation (b) Curvature radius and angle

Fig. 7. One step turning

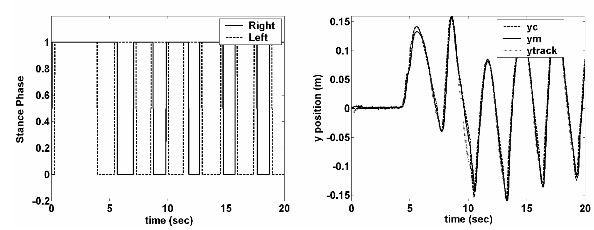
Therefore, in order to navigate normal pathways that exist in real environments, the relatively small angle for one step can simulate normal circular pathways. Therefore, the proposed locomotion can be applied to normal pathways with the limited curvature larger than 2 m. If a human try to turn more than 20°, the controller gives warning.

V. Walking Experiments

To implement the real walking interactions with the proposed interface, the safety of a user should be guaranteed all the time. Therefore, the parallel bar is constructed for user to keep balance of their bodies during walking. Initially, subject stands on the interface device about 3 seconds. During that period, both left and right limbs contact ground. Then, the left limb moves forward during swing phase, while the right limb remains still during single stance phase. Fig. 8 show real experimental results of human walking using the proposed control algorithm for level ground. Fig. 8(a) shows the left and right stance periods. It should be noted that there was always double limb stance throughout walking experiments even though the double stance duration varied for gait cycles. Fig. 8(b) shows the tracker input y_{track} for back-and-forth motion, and the command input y_c for back-and-forth motion. Fig. 8 (b) also shows that the interface device is tracking well the trajectory of the command input. During swing phase, the platform could trace the tracker positions with acceptable errors and during stance phase, the backward motions with linear average velocity of the previous swing phase allowed smooth home positioning without any significant jerks. It should be noted that the ratio of stance and swing phase during general walking with the proposed interface was very similar to normal gait cycle.

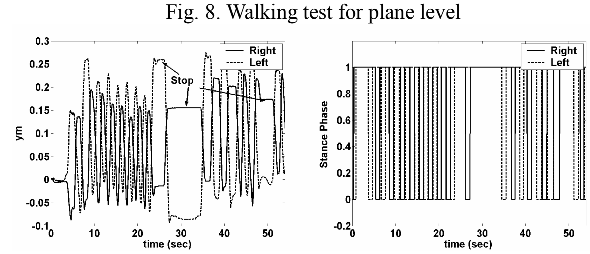
If the user doesn't want to continue next step after double stance period and holds his limbs at the platforms, the stopping motions of the interface were generated very naturally without additional efforts. Similarly, the starting of the walking was very natural. Since the platforms sustained the current positions when user's feet were on the platforms, the proposed walking algorithm allowed the natural stopping and starting of the walking. Fig. 9(a) shows that a user started walking with his attention, then stopped first with left limb stop and then with right limb stop, and then again restarted the walking. Fig. 9(b) shows the resultant stance periods of two platforms during walking, stopping, and restarting. It should be noted that even though the platform can follow the foot, the user could change his speed for each gait cycle. Therefore, the home positioning by using the previous average velocity during swing phase can cause offsets of neutral positions from initial positions as shown in Fig. 9(a). Since the locomotion interface has limited workspace, the home positioning is inevitable for continuous walking. Therefore, neutral positioning algorithm discussed in section III is implemented during double stance phase. Fig. 10 shows the subject can walk omni-directionally on planar surfaces for x, y, and yaw directions. Also, their neutral positions recover and go back to initial positions. Even though the forward direction (y axis) of foot trajectories during walking is most dominant, the lateral (x) and yaw rotations also change continuously within certain bounds. For upright motions, the desired command of the lateral and yaw motions are set to zero since the platform with large size can compensate these motions. On the other hand, for foot turning motions, the lateral and yaw motions as well as forward direction are used to follow omni-directionally.

Fig. 11 shows the results of turning motions. Fig. 11(a) shows the left and right yaw motions of the platforms and Fig. 11(b) shows the estimated instant body angle at each step that is updated at each foot's contact instance. The body angle will be transferred into virtual environments.



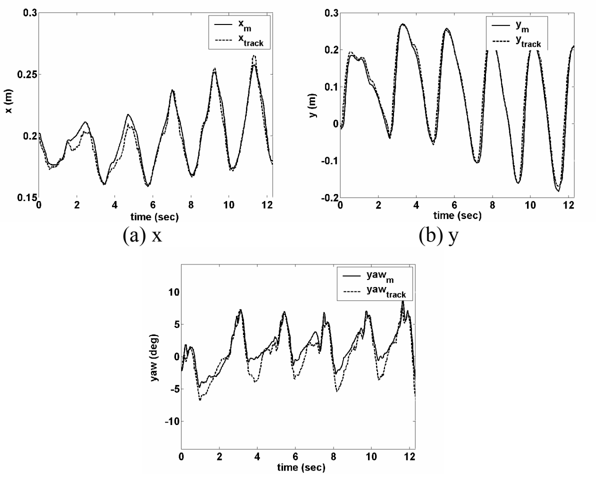
(a) Stance phase (b) y_c, y_m, and y_{track}

Fig. 8. Walking test for plane level



(a) y_m (b) Stance phase

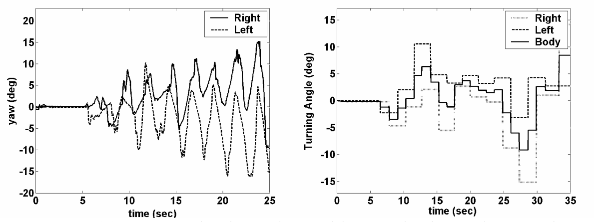
Fig. 9. Starting and stopping during walking



(a) x (b) y

(c) yaw

Fig. 10. Planar omni directional walking for 3-axis (Right platform)



(a) yaw (b) the estimated instant body angle at each step

Fig. 11. Turning motions

VI. DISCUSSIONS & CONCLUSIONS

This paper presents a novel walking control algorithm using a omni-directional locomotion interface composed of dual-planar parallel robot. The suggested dual-planar parallel robot can allow omni-directional walking with relatively simple structure. In order to apply the suggested device for a natural walking interface, the walking motions of human foot are sensed by magnetic type motion tracker compensated by position and orientation calibration, and micro switch system. Then, a walking control algorithm is suggested to satisfy normal gait conditions that have single and double stance phase, and swing phase. With the consideration of the double stance phase, the interface allowed natural starting and stopping of walking according to a user's intentions. The turning angle of the user body was estimated by average angle of two yaw motions of foot at each contact moment. From experimental results of upright walking interactions at level ground, a subject can walk naturally and change walking speed according to his own intentions, and stop and start safely without any considerable disturbances. For turning motions, since the two platforms may have possibility to collide each other when the platform follow the human foot, the yaw motions limitations of 20 degree for each platform were given to each platform. However, since the general pathway doesn't need to change body motions abruptly, the suggested interface can be applied to normal walking interface with general virtual pathways. The maximum achievable velocity of the locomotion interface is within 1.2m/s which is smaller than treadmills due to the more complex mechanical structure and recentering motions. The Future research will apply the suggested locomotion interface to lower limb rehabilitation after evaluations by gait analysis.

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