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Design for Locomotion Interface in a Large Scale Virtual Environment ATLAS: ATR Locomotion Interface for Active Self Motion

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Abstract:

In this paper, we focus on the sense of locomotion, in particular, the sense one feels while walking in a large space. Walking is the most basic way of moving around, and a lot of information can be obtained by doing so, e.g., sensing, hardness, humidity, and so on of the space. The locomotion interface we have developed is named ATLAS (ATR locomotion interface for active self motion). Our design goal was to eliminate the need for a walker to "learn" how to walk and for equipping the walker with obstructive sensors. We employ a treadmill approach for ATLAS. In the initial trial state, ATLAS can estimate the working speed from the walking motion visually, and control the speed of a belt to synthesize the real feeling of walking in a virtual space. First, we describe related works of locomotion interfaces and our design. Next, we show the method utilized for motion analysis and how to control the belt speed. Finally, we conclude with a description of our first trial ATLAS and the experimental results.

Introduction

Virtual reality is expected to allow us to experience new things that cannot be experienced in real life. VR can simulate any point in time, any position in space and any object. For example, it can allow us to face an extreme situation where the real situation would probably be life-threatening due to some physical limitation: an extremely high or low pressure or temperature or a micro or megaworld. It can also reproduce a past scene, enabling dim vistas of our childhood to be opened up.

At ATR-MIC, we are investigating communications between humans themselves, and between humans and machines. Our group has been applying VR to generate suitable communications environments and developing a VR interface. As one of our targets, we are focusing on the sense of locomotion, in particular, the sense one feels while walking in a large space.

Walking is the most basic way of moving around. By doing so in the areas we live, we can find out much information, like the scale, hardness, humidity, and so on of the space. Some VRML viewers, called “walkthrough simulator”s, allow a user to move around a virtual world on the screen. However, they don't give the user the sensation of walking because the user controls merely the direction and speed of the viewing point by using a mouse, like driving a car without realistic feedback for locomotion.

In this paper, we describe the development of a locomotion interface named ATLAS (ATR locomotion Interface for active self motion). Our design goal was to eliminate the need for the user to "learn" how to walk and to equip obstructive sensors. We employ a treadmill approach for ATLAS. With our first trial ATLAS, we can estimate the working of the user speed from the motion of his/her feet visually and control the speed of a belt to synthesize a real feeling of walking in a virtual space. First, we describe related works on locomotion interfaces and our design. Then, we show details of the motion detection unit and those of the control system. Finally, we present our first trial ATLAS and experimental results to show the effectiveness of the method.

Related Works and Design Concept of ATLAS

When we want to go somewhere, we can choose the most suitable method for getting there: by foot, bicycle, car or airplane. Many applications have been developed and a lot of research has been done to date to simulate the feeling of locomotion. Most of them use a vehicle simulator as a training tool or as entertainment, and they are nearly complete. In this paper, we limit our discussion to a locomotion interface for self motion, i.e., walking or running. As a start, we describe previous research related to locomotion interfaces for self motion. Next, we present the design concept of ATLAS.

Locomotion Interfaces in VR

Generally, a locomotion interface should cancel the user’s self motion in a place to allow the user to go to anywhere in a large virtual space on foot. Several devices have been studied up to now and we classify them according to the way in which they cancel motion.

Treadmill

A treadmill is used to cancel the user's motion by moving an infinite belt in the opposite direction. The main advantage of using a treadmill is that the user does not have to wear obstacle devices.

One major problem, however, concerns how to control the belt speed so as to keep the user from falling off. In the case of a motor driven treadmill, the system has to adjust the belt speed based on the user's motion. Using a passive treadmill, in contrast the belt is driven by balancing the user’s weight, so the user never falls off the belt. This approach, however, can generate a flat surface only.

Another major problem is how to change the walking direction. Brooks [3] and Hirose [10] employed a handle to change the direction. Mechanical 2D treadmills have been proposed. As a motor driven treadmill, Iwata [13] developed a 2D infinite plate that can be driven in any direction and Darken [5] proposed an Omini directional treadmill using mechanical belt. As a passive treadmill, Eyre [7] proposed a Spherical Projection System employing a huge semitransparent sphere. A user can walk inside it and it acts a visual screen for projectors, also.

Active Footpad

This method also does not to require the user to wear obstacle devices and can simulate various terrains. Latham [16] is developing OmniTrek, which uses two footpads. These footpads are slightly larger than the size of a human foot. They track the feet of the user quickly and cancel the user’s motion so that s/he does not go out of the device. Roston [18] proposed a Whole Body Display that allows the user to walk on stairs, on sand, in mud and so on. Generally footpad has to support the user's whole weight and track the foot's motion quickly, therefore it requires sufficient rigidity and a wide band width.

Sliding Interface

Iwata [12] developed a series of sliding interfaces. The user wears special shoes and a low friction film is put in the middle of the soles. Since the user’s body is supported by a harness or rounded handrail, the foot motion is canceled passively when the user walks. The system measures the foot motion and changes the user’s view together with walking motion.

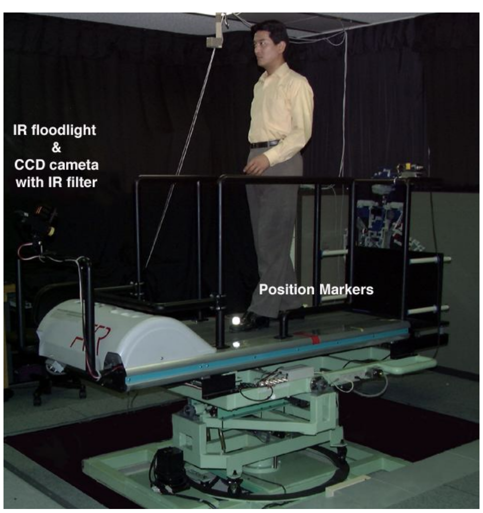


Fig. 1 First trial ATLAS

Pedal Interface

Using a bicycle, the user's motion is different from walking, however the complicated walking motion is simplified and can be measured easily by computer. Brogan [2] developed a pedal interface for people training for bicycle road races. Ensor [6] developed a VRML based bicycle simulator.

Other Methods

Some research has related the gesture of walking to locomotion. Choi [4] developed CyberBoots. Four pressure sensors are put on the sole of each foot and a gesture detecting system using fuzzy logic outputs motion patterns. Kadobayashi [14] developed a gesture interface, called VISTA Walk, that detects the user’s motion visually. Kobayashi [15] reported a similar device that measures the position of the center of balance by a sensor tile.

They translate gestures into commands for moving in a virtual space, so the user has to learn how to walk in a virtual space in advance.

Design Concept of ATLAS

Our goal was to develop an intuitive locomotion interface for walking with the least amount of equipment on the user's body. To achieve this, we employ a motor-powered treadmill for ATLAS. (Figure 1) ATLAS consists of a remodeled commercial treadmill and a motion platform with three axis.

As mentioned above, we have two problems: how to control the speed of its belt and the walking direction. In this paper, we solve the former problem. In the following section, we discussed a method for human gait detection without an obstacle sensor and a method for controlling the speed of the belt.

Gait Estimation for Locomotion Interface

Ideally, if the system could drive the belt at a speed equal to the walking speed in the opposite direction without a time delay, the walker would be kept in place. However, it is difficult to sense walking speed directly, and a mechanical delay can not ignored, so the system has to adjust the belt speed by referencing the user's position and walking speed in some way.

Research on human gait analysis has been done in the area of orthopedics and biomechanics. Sensor tiles [18,20], body acceleration meters [1,8] and visual methods [9,21] have often been used. Whereas most of them record data at once, and analyze it off-line, we have developed a new method that can visually estimate the walking position and speed from the toes' motion in real time. Toe motion can be easily measured with a computer vision system without the need for contact.

Here, we discuss the relationship between walking speed and the human gait using the results of measured walking motion on a flat floor.

Experimental Method

We used a magnetic position sensor called Fastrack™ to record the motions: both of the walker's toes and the waist, which represents the walker's body position. Figure 2 shows the coordinates in the target area. Subjects were asked to walk from a start line to an end line. The distance of the path was six meters. Six subjects participated, five men and one woman, and they were all in their twenties or thirties. The walking pace was controlled by sound at 120, 96 and 72 steps/min. We asked for three trials at each pace, so we got 54 samples in total.

Since the effective area of Fastrack™ was limited within the hemisphere of a 150cm radius around the sensor, we arranged the measurable space at the middle point of the path. The sampling rate was

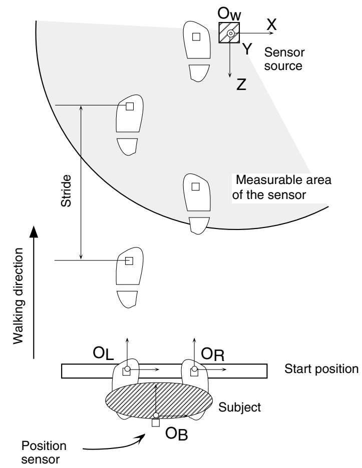


Fig. 2 Experimental setup

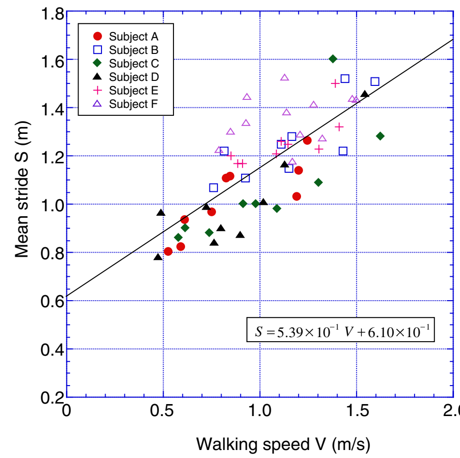


Fig. 5 Speed versus mean stride on ground

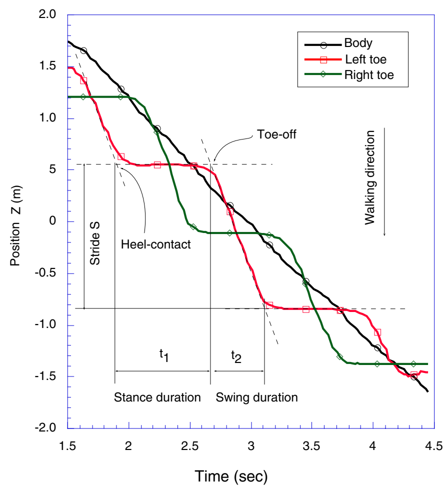


Fig. 3 Typical walking motion

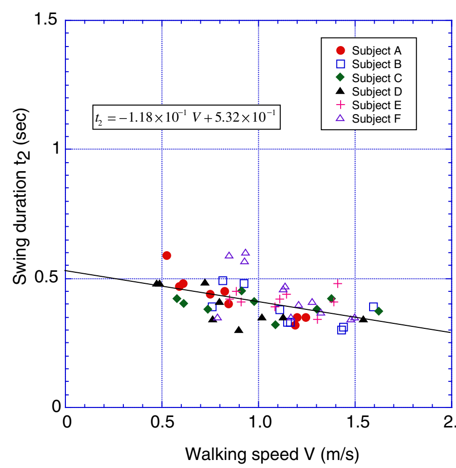


Fig. 6 Speed versus swinging duration on ground

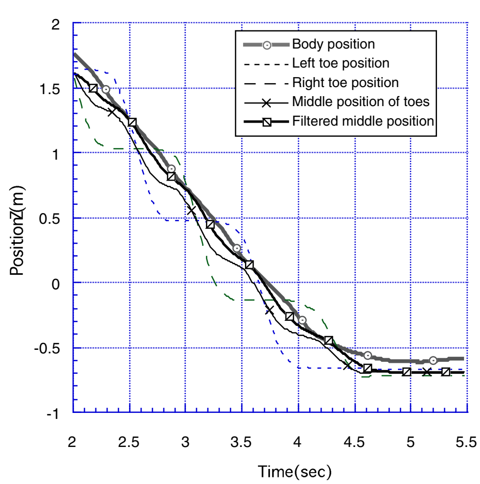


Fig. 4 Estimation of walker's position on ground

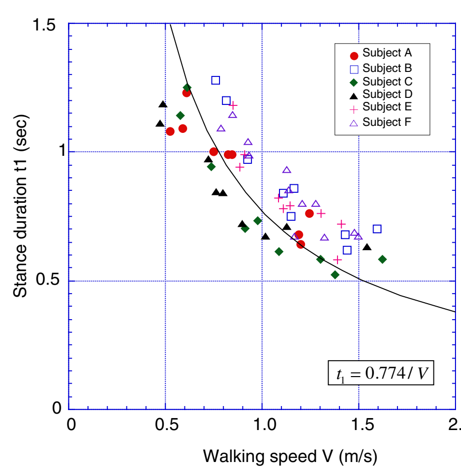


Fig. 7 Speed versus stance duration on ground

40Hz and the precision of the data was 0.8mm.

Figure 3 is a typical time series graph that indicates the motion of the body and two toes. We manually worked out the average stride S, the duration of stance phase t_1, the duration of swing phase t_2, and the walking speed V from them. Here, the "Stride" is the distance between the heel of a footprint and the toe of the previous footprint of the same foot. "Stance phase" is the phase in which the foot continues to touch the floor. "Swing phase" is the phase during which the foot is swinging forward.

Estimation of Position

First, we estimate the body position from the toe position. Figure 4 shows the time series graph of three position data: body, left toe and right toe, and two calculated results: middle point between toes and filtered results of the middle point. Comparing the measured body positions, the middle point shows a 0.5Hz pulsatory motion that was caused by the repetition of the swing and stance phases. Therefore we processed a LPF with a cut off frequency of 0.2Hz to apply this calculated value. Body motion is not as quick as feet motion, so the delay by the LPF can be ignored. As shown in the result, the filtered result followed the body position well. In the trial ATLAS, we employed this method to estimate the position on the treadmill.

Estimation of Speed

Figure 5 shows the walking speed V versus mean stride S from all trials. Markers represent the subjects. Using an analysis on the variance of S per subject, the subject was a significant factor ($F(5.48)=8.13$, $p<0.001$.) Focusing on one subject, the stride becomes longer in proportion to the walking speed, but the coefficient of the regression line greatly depends on the subject. Therefore, it is not enough to use stride for speed estimation.

Figure 6 presents the walking speed versus the mean duration of swing phase t2. Makers are the same as for the previous results. An analysis on the variance of t2 per subject showed that the subject was not a significant factor ($F(5.48)=1.02$, $p<.419$).

On the other hand, Figure 7 shows the walking speed versus the mean duration of stance phase t1 from every trial. An analysis on the variance of t1 per subject showed that the subject was not a significant factor ($F(5.48)=0.54$, $p<.743$).

The regression lines of V to t1 and t2 are indicated in the graphs and following equations.

$$t_2 = -1.18\times10^{-1}\ V + 5.32\times10^{-1} \tag{1}$$

$$t_1 = 7.74\times10^{-1}\ V^{-1} \tag{2}$$

These results indicates that the duration of stance phase t1 is in inverse proportion to the walking speed, and the duration of swing phase t2 is also proportional to walking speed. Comparing the response, the relation between t1 and V is better than that between t2 and V, therefore, we employed speed estimation using the duration of the stance phase on the treadmill.

Design of the Speed Controller for the Treadmill

Based on the previous results, we built a speed controller for the trial ATLAS. The goal of the controller is to keep the walker at a point on the treadmill by adjusting the belt speed using visually obtained gait parameters.

Before starting this discussion, we will give some assumptions and definitions. First, the belt speed and the walker's toe positions and speeds can be measured in real time. A detailed method for obtaining them visually is taken up in the next section. Next, comparing the toes' motion and belt speed, the walking phase can be detected automatically and the speed estimation unit updates its output when the stance phase is switched to swing phase. Furthermore, the first order hold sampler outputs estimated walking speed to the controller in real time. Next, figure 8 shows the definitions for this section. The upper left character represents the coordinate with which they are referenced. "w" is the coordinate "world" and "t" is the coordinate "Treadmill" fixed on it. ${}^{w}V_{belt}$ is the belt speed, ${}^{w}V_{walker}$ is the walking speed. ${}^{T}X$ is the walker's position on the treadmill. ${}^{w}V'_{walker}$ is the estimated walking speed, and ${}^{w}\hat{V}_{belt}$, ${}^{T}\hat{X}$ are desired values.

The aim of the controller is to achieve automatic regulation for ${}^{T}X$ even if the walker changes walking speed, provided that the transit response of the walker's position is the critical dumping and the acceleration of the belt speed is limited to prevent the walker from falling down.

As mentioned previously, ideally the belt speed should be equal and in the opposite direction to the walking speed. However, the treadmill

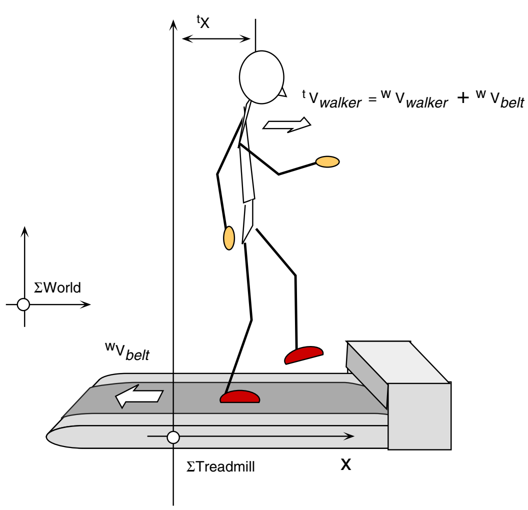


Fig. 8 Dynamics of ATLAS

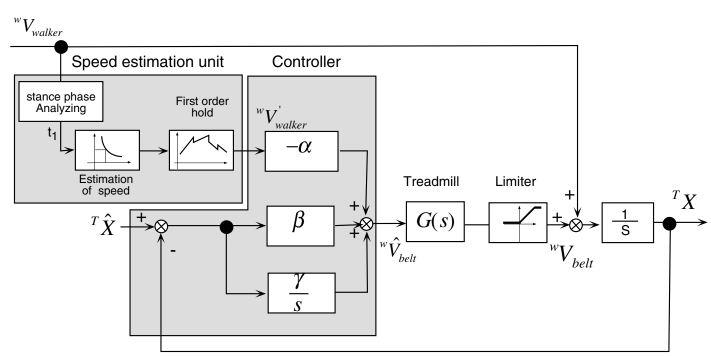


Fig. 9 Block diagram of speed controller

has a mechanical delay and our speed estimation unit update output once every step. Therefore our speed controller employs a primary feedforward using the estimated walking speed and PI feedback unit using the estimated walker's position on the belt to cancel the offset caused by error of the speed estimation unit. Figure. 9 shows a block diagram of the controller. Here, G(s) is treadmill and α, β, γ are the gain for the each element of the controller.

When ${}^T\hat{X}$ is equal to the origin, the transfer function is shown in equation (3).

$$ {}^T X = \frac{1}{s}\left[{}^w V_{walker} + G(s)(\alpha\, {}^w V'_{walker} + \beta\, {}^T X + \frac{\gamma\, {}^T X}{s}) \right] \qquad (3) $$

where the nonlinear elements are ignored. The feedforward gain α should be the inverse function of G(s) ideally, however this is impossible. As shown in the block diagram, the system contains a few nonlinear elements, so it is difficult to find the out optimal parameter by mathematical analysis. In the trial ATLAS, we adjust α to 0.6 within the limit of the conditions.

The offset that is caused by the insufficient feedforward gain and estimation error can be compensated by the feedback elements. We employ a typical PI feedback in the trial system. Adjusting gain β, γ for PI feedback, we considered the stability of the feedback system. First, we regard ${}^w V_{walker}$ as noise to the feedback loop, characteristic equation is taken as equation (4).

$$ 1 + (\beta + \frac{\gamma}{s}) G(s) \frac{1}{s} = 0 \qquad (4) $$

By considering that G(s) can be modeled as the first order system with dead time, G(s) can be written as equation (5) by Pade approximation.

$$ G(s) = \frac{e^{-0.09s}}{1+0.1S} = \frac{1}{1+0.1s} \cdot \frac{1-0.045s}{1+0.045s} \qquad (5) $$

Where parameters are determined from the trial ATLAS. Putting equation (5) into equation (4), we apply it into Routh's method. As a result, Figure 10 indicates that the feedback works well when gain β and γ are within the shaded area. As β becomes larger value, the peak of the response of the walker's position decreases. As γ becomes a larger value, the overshoot converges faster. However, stability is gradually lost as β and γ become large. By considering that transit response should be the critical dumping, the shaded area in Figure 10 will be reduced. We decide the gains by making an adjustment with the trial ATLAS within the results, and we put β=6, γ=5 under this limitation.

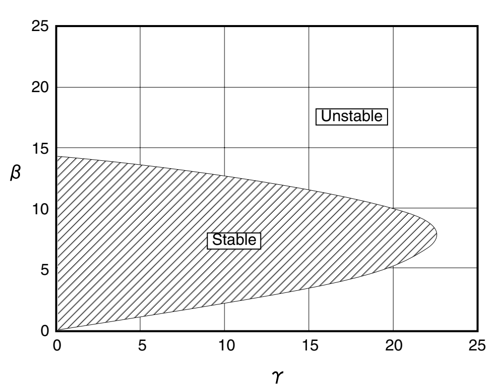


Fig. 10 Feedback gain for stable convergence

Trial ATLAS

Overview of The Trial ATLAS

We built the trial ATLAS using the previously mentioned method. Figure 11 gives an overview. We arranged a CCD camera with an infrared light filter and an infrared lamp in front of the treadmill. Putting small IR reflection markers on the walker's each toe, the markers' points, in short toe position, can be measured while the subject walks on the belt without having to be concerned with noise from other light source such as the ceiling lamp, and so on. We employed a video tracking system called QuickMug™ manufactured by OKK. QuickMug™ can track eight bright markers simultaneously at 60Hz. Since the results of one trace produce a 2D data set, so we assume that the walker's feet are always on the belt. Under this assumption, the system translates the 2D tracking data into the positions of the feet on the belt. The accuracy of tracking is 0.3cm in the worst condition. Furthermore, we use Fastrack™ to measure the walker's head direction, to support the head tracked visual images as an optional extension.

Our altered treadmill is a commercially available product. The permissible walking area of the belt is 145 cm (D) x 55 cm (W). The belt speed can be controlled by a PC, from 0 to 4.0m/sec continuously, and its time delay is 0.09 sec and time constant is 0.10 sec within walking speed. The treadmill is arranged on a custom made motion platform with three axes. It can be tilted and can maintain the walking surface in any direction.

Two computers, a PC and a SGI ONYX™ control these devices.

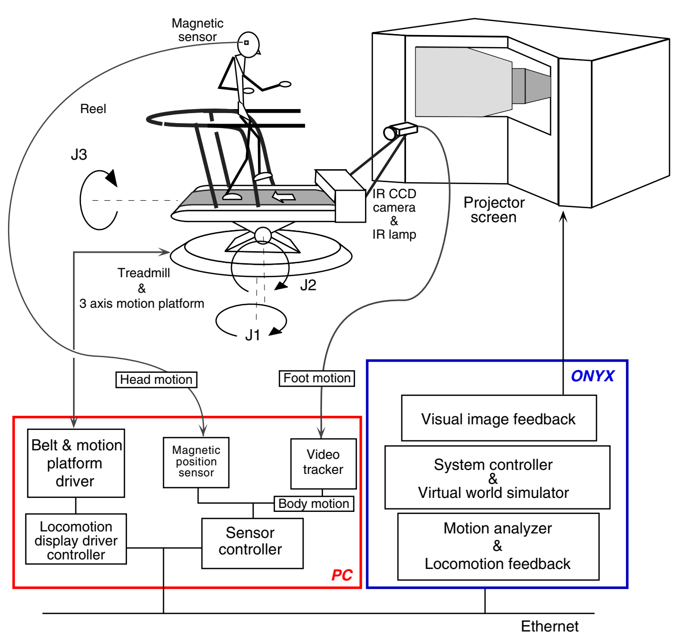


Fig. 11 Overview of trial ATLAS

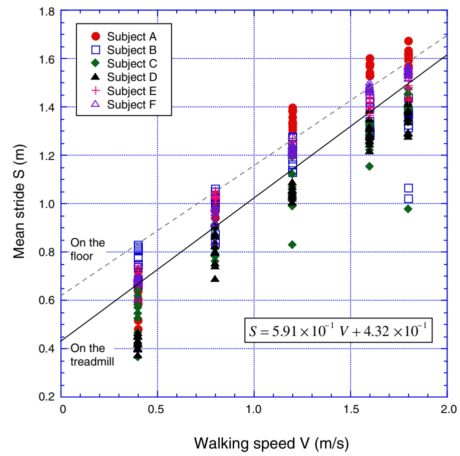


Fig. 12 Speed versus mean stride on ATLAS

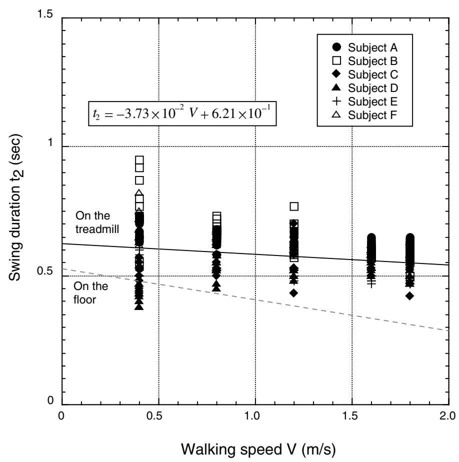


Fig. 13 Speed versus swinging duration on ATLAS

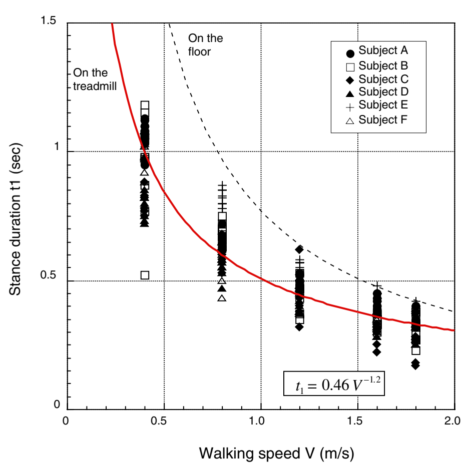


Fig. 14 Speed versus stance duration on ATLAS

The PC acts as an interface I/O for the video tracker, the magnetic tracker, the treadmill, and the motion platform. All data is exchanged via ethernet.

The motion analyzing subsystem in the ONYX™ distinguished walking phases by comparing the belt speed and the toe speed. The controller described in the previous section is built into the locomotion feedback. These subsystems operated at 60(Hz).

A virtual world simulator subsystem maintains a database for a large-scale virtual space and manages the user's position in the world. A visual image feedback subsystem generates images of the world on a projector screen in front of the walker.

Results of The Trial ATLAS

In this section, we evaluate the proposed method by using the trial ATLAS.

Adjustment of Speed Estimation Unit

First, we confirm the motion analyzing subsystem for the treadmill. Since previous results were obtained from walking on the ground, it is not to be denied that walking on the treadmill is as same as walk on the ground. Here we measured "Stride", "Duration of stance phase" and "Duration of swing phase" on the treadmill again.

Six subjects were asked to walk on ATLAS. They were same subjects who participated in the previous experiment. One important difference was that the belt speed was fixed at 0.4, 0.8, 1.2, 1.6 or 1.8 (m/sec), meaning that walking was not purely a self motion. Using the motion analyzing subsystem of ATLAS, ten steps under each condition were measured.

Figures 12, 13 and 14 show the results for the motion analyzer of ATLAS. The axes and markers were the same as in Figures 5, 6 and 7. The black lines indicate the regression functions for the result. The dotted lines are from the results on the ground for reference. Compared with the results on the flat floor, the output from the motion analyzer showed the same tendency as the results on the ground. The stride on ATLAS is observed to be a little shorter than the stride on the ground. The duration of the swing phase is longer than the same value for walking on the ground and the duration of stance phase is shorter. This is due to the difference in the algorithm of phase detection. Therefore, we proofread the equation of the speed estimation using the results.

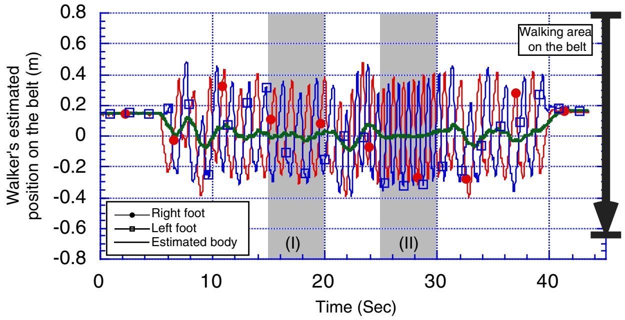
$$t_1 = 4.6\times10^{-1}\ V^{-1.2} \qquad (6)$$

When the motion analyzing unit fails to distinguish phase detection and output a shorter stance duration, the estimated speed is too fast. Therefore the output from the speed estimation unit is limited in maximum 2.0 (m/sec). This estimation parameter is used in the following experiment.

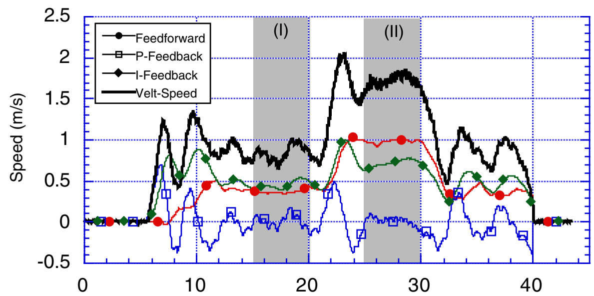
Results from Walk After the Block Task

We conducted a simple experiment to the examine controllability of walking speed with "walking after the block task." On the screen in front of ATLAS, two blocks were displayed, and they moved from the bottom to the top of the screen. One was controlled by the system, and the other block was synchronized with the subject's motion. When the subject walked faster, the second block moved faster. In this condition, subjects were asked to walk after the first block at the same speed. The system controlled block began to move at 5sec after the task started. The initial speed of the block was 0.8 m/sec. When 20sec passed, it accelerated to 1.6m/sec, and slowed down to 0.8m/sec at 30sec. When the task clock reached 40sec, the block stopped.

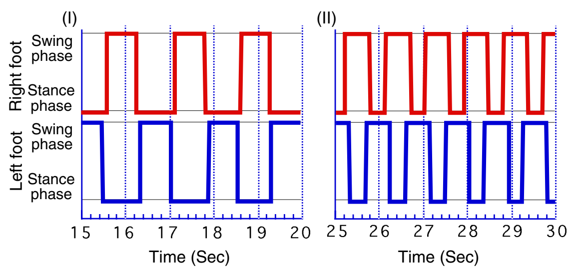
Figure 15 shows a time series graphs of one typical result on the



(a) Time vs. walker's position on the belt



(b) Time vs. belt speed, feedbacks and feedforward



(c) Results of motion analysis

Fig. 15 Typical result of walking motion on ATLAS

trial. Figure 15(a) shows the estimated subject's position and the repeated motion of the subject's toes on the belt. The walking direction was minus axis in the graph and the walkable belt area is illustrated on the right side. It shows that the subject was always kept within 0±0.1m even when the walking speed changed while walking. The belt speed and output from feedforward and two feedback elements are shown in Figure 15(b). Since the subject's position was kept in place, the belt speed can be regarded as the walking speed. Therefore, it can be seen that this subject could walk after the system controlled block well in the trial. Observing the transit response, the subject's position shows a peak when he speeded up at 21sec. At that time, the PI feedback responded faster than feedforward, and soon the PI-element took turn primary control to the feedforward element as we has designed it. Figure 15(c) shows the results of the motion analyzer during the two shaded periods in Figure 15(a) and (b). As the walk became faster, the detected duration of the stance phase became shorter.

We used twelve subjects: Two of them were experienced subjects and the others were novice to the ATLAS. They were all in their twenties

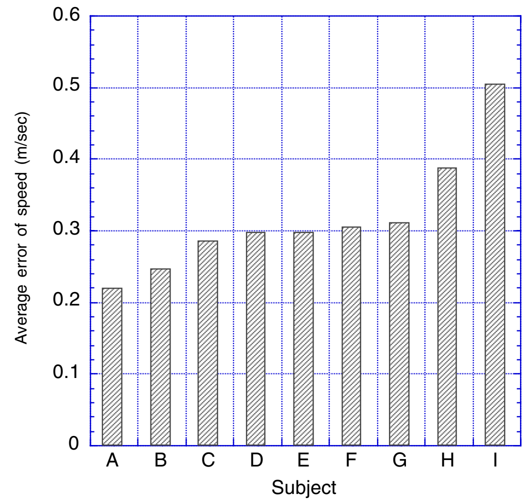


Fig. 16 Experimental results

or thirties. Before the test, we gave short instructions about ATLAS and left them to use it freely until they could start, walk and stop on ATLAS. At this training phase, three novice subjects were finally not able to walk and gave up on the experiment. They could not walk at a constant speed as they desired and all showed a reciprocating movement on the belt on the belt while walking.

After the training phase, we asked them to walk after the block ten times. The first five trials were ignored as a training phase for the task, then, in the latter five trials, we measured the difference in speed between two blocks, because we focused on walking speed controllability.

Figure 16 indicates the average of square rooted difference of the speed in each subject. Here, A and B are experienced subjects, so their results were regarded as the optimal value. It is likely that the novice subjects C, D, E, F, G, H were able to control their walking speed as well as the experts. Subject I only had trouble controlling the walking speed.

The subjects who gave up on the trial were able to maintain their walking speed on the ATLAS when gains of the feedback and the feedforward were reduced. Therefore, it is possible that the reason for this is that the stability of the positional feedback loop that includes both the subjects and the ATLAS was lost in the trial. Since we cannot say for certain about the feedback including a subject, we left this problem as a subject for future works.

Moreover, some subjects reported that it was difficult to stop walking. ATLAS monitors toes motion constantly, and manages the control mode: staying, starting, walking and stopping automatically. When the walker intends to stop walking, s/he will stop her/his foot motion usually. It takes 0.1sec for ATLAS to detect this motion, and it takes almost 0.1sec to stop the belt because of mechanical delay. Totally, belt runs for 0.2sec after the walker stops. Therefore, the walker has to reduce speed enough before the stop motion and this requires some skill on the part of the walker. A solution to this is an important subject for future work also.

Conclusion & Future Work

If we focus only on the effectiveness of the moving speed in a virtual space, we should choose a beam-like method to change the standing point.

The reasons why we walk using our self motion are as follows: concerns about our heath, to become refreshed, to train ourselves, to observe or contemplate things, for rehabilitation purposes, and so on. Here, walking is not the object but a method. From this point of view, it should be noted that a locomotion interface should offer the feeling of a real walking motion to the user as possible.

The purpose of our research is to obtain such an interface and, in this paper, we have proposed a locomotion interface that uses a treadmill activated by the user's self motion. The treadmill method has two problems: how to control the speed and how to control the direction of walking. By only putting two small IR markers on the toes, we solved the first problem. Our method can estimate the walking motion and adjust the belt speed of the treadmill to keep the walker in place on the belt. These sensors never disturb the user's motion. We have built a trial model named ATLAS, and have confirmed our method from the experimental results.

The experimental results showed that even novice users were able to control their walking motion after a few training session. On the other hand, a few of them could not control this motion very well. One reason for this is that our proposed method does not have flexibility toward different personalities. Grieve [9] reported that the relation between the stance phase and the walking speed differs according to generations. We have to develop way to adjust such system parameters in future.

As for the second problem concerning the walking direction, we realized the need to direct the walking by changing the face direction (measured by Fastrack™ with the trial model). Needless to say, however, this is not the natural way that we are aiming for. Therefore, we are now investigating a solution with a more intuitive approach.

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