Online Appendix to: CyberWalk: Enabling Unconstrained Omnidirectional Walking through Virtual Environments

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APPENDIX

1. A SHORT HISTORY OF OMNIDIRECTIONAL LOCOMOTION INTERFACES

The requirements for enabling real walking through a virtual environment (VE) depend on its size. For small VEs, which fit within a room, it may be sufficient to track the position and orientation of the head of the user and allow him/her to physically move around through the VE. Visual rendering, on a head-mounted display (HMD) or CAVE-like projection system, can be updated according to the measured head movements [Meilinger et al. 2007; Campos et al. 2007]. Larger VEs can be accommodated by using redirected walking techniques, such as applying gains to translations and/or rotations and having users walk on curved paths while simulating a straight trajectory in VR [Engel et al. 2008; Razzaque et al. 2001; Razzaque et al. 2002; Steinicke et al. 2009; Steinicke et al. 2010]. However, for large VEs, this quickly becomes impractical or even impossible, unless the trajectory that the user will take is known beforehand. Instead, we need a locomotion interface that keeps the user within a confined space, while allowing movement through a much larger VE. Linear treadmills allow the user to walk for extended periods of time while staying in the same place [Souman et al. 2010; Christensen et al. 2000; Minetti et al. 2003; Hollerbach et al. 2000; Noma et al. 2000], but turning has to be implemented in ways that many users find unnatural. In some implementations, turning is based on the lateral position of the user on the belt, or on the orientation of the head and/or torso (the latter seems to work best [Vijayakar and Hollerbach 2002]). Alternatively, the entire treadmill can be turned when the user's intention to turn is detected [Noma et al. 2000]. However, in all of these methods the restriction to a linear treadmill requires the user to come back to the original straight ahead direction after the visualization has turned sufficiently. This is not necessary in another type of locomotion simulation, where the user steps in place and is free to turn in any direction [Templeman et al. 1999; Slater et al. 1995; Slater et al. 1993]. The stepping movements are translated into forward motion in the visual display. However, users have to concentrate on the stepping in place itself to make it work, making this a cost-efficient but at the same time less natural way of simulating real locomotion [Templeman et al. 1999; Usoh et al. 1999].

Some of the first omnidirectional locomotion interface designs stayed close to the stepping in place concept. In the Sarcos Biport, the feet of the user are supported by two individually controllable platforms, each with three degrees of freedom for position [Hollerbach 2002]. Iwata's GaitMaster uses a

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similar design [Iwata and Yoko 1999]. Although the feet can be turned to a limited extent, changes in walking direction is implemented by turning the entire interface. This makes omnidirectional walking less natural than desired. Curved paths are possible with a more recent device, which has six degrees of freedom for both foot platforms [Yoon et al. 2009; Yoon and Ryu 2006]. However, users still cannot change their walking direction arbitrarily. In addition, the required stiffness and safety measures limit the possible walking speeds. An advantage of these stepping platforms is the possibility to simulate uneven terrain, taking walking to three dimensions.

Other designs have used passive systems to keep the user in the same place. One implementation of this principle is offered by the Virtusphere (Virtusphere Inc.). The user walks within a large sphere, which is driven by the user's steps. The combination of surface curvature and gravity automatically keeps the user in the center of the sphere. While the Virtusphere is supported by mechanical rollers, the similar Cybersphere rests on a pressured air cushion, which reduces friction [Fernandes et al. 2003]. Another special feature of the latter design is that the sphere is made out of translucent material, allowing for the back-projection of graphics from the outside. In the Virtusphere, visualization is only possible via a head-mounted display with wireless data transfer. Instead of using an entire sphere, a spherically curved surface consisting of an array of metal balls has also been used to passively center the user on the platform [Huang 2003]. Despite the elegant principle of these passive designs, obviating the need for complicated control algorithms, an obvious disadvantage is the curvature of the walking surface. Moreover, the passive nature of the system makes rapid changes in walking speed and direction unnatural and undesiredable.

Recently, the idea of having the user walk on an array of small balls has been taken a step further in an active locomotion interface for humanoid robots [Nagamori et al. 2005]. In this system, the user walks on a ball array that is driven by a normal treadmill belt from underneath. The belt is mounted on a turntable, allowing for rotational as well as translational movements. Because the original implementation was too small and too slow for a human to walk on, we have implemented the same design in a larger prototype [Schwaiger et al. 2007a, 2007b]. Testing several control schemes with this prototype, we realized that it has two main problems. First, to allow for natural walking, the walking surface has to be scaled up to several meters in diameter, which increases the number of balls needed to create a comfortable walking surface in a quadratic fashion. As each ball exerts its own friction on the surface that keeps it on the belt, a larger number of balls implies a larger amount of friction. This may be remedied by using separate bearings for each ball, but only at the expense of exponentially increasing costs and complexity of such a device. Second, and more importantly, keeping the user centered on the walking surface will always entail rotations. If the user changes walking direction in order to execute a turn, the belt has to be rotated underneath the ball array, causing the user to be rotated around the vertical axis as well, even while aiming to walk along a straight line after the turn (due to the inherent system lag). Since humans are very sensitive to these imposed rotations [Benson 1989], this will likely disrupt the immersiveness of walking in VR.

So far, the most successful attempts at creating an omnidirectional locomotion interface have been based on the standard treadmill concept. Darken et al. [1997] created a two-dimensional treadmill by essentially putting one treadmill inside another, at a 90deg angle. Both directions consist of assemblies of freely rotating rollers, one orthogonal to the other. Actuating the rollers in one layer produces motion in one direction; actuating the other layer produces motion in the perpendicular direction. Together, the two layers can create motion of the walking surface in any direction. The treadmill actively responds to movements of the user, keeping him/her on the center of the walking area. To this end, the position of the user is measured by means of a tracking arm attached to the user's lower back.

A related concept has been implemented in Iwata's Torus treadmill [Iwata and Yoko 1999; Iwata 1999]. Rather than using rollers, one movement direction exists of 12 normal belts, which are mounted

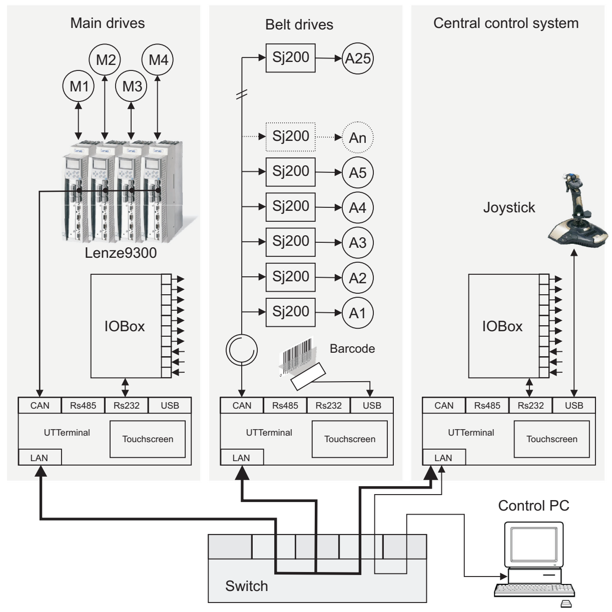

Fig. 10. Lower level treadmill control system.

on chains running in the orthogonal direction. As with the Omnidirectional treadmill, combined actuation of belts and chains can produce motion of the walking surface in any direction, thereby keeping the user close to the center of the platform. The position of the user is measured by means of sensors on his/her knees. The treadmill only responds to user motion once he/she steps outside a dead zone in the center.

The main disadvantage of the omnidirectional/torus treadmill concept is that it involves big, complicated machines, with a large number of moving parts. In order to achieve sufficiently high accelerations, the device must be driven by powerful motors, which involves real safety risks. Darken et al. [1997] reported that users can walk on their device with speeds up to 2m/s. However, this comes at the cost of high levels of auditory noise and of wear and tear on the machine. The Torus treadmill is capable of a speed of 1.2m/s. Since the walking surfaces of both devices are relatively small (1.0×1.0m for the Torus treadmill; 1.3×1.3 m for the Omnidirectional treadmill), accelerations of the treadmill must be relatively high in order to keep the user on the platform at all times, thereby disturbing normal walking behavior. Since Darken et al.'s publication in 1997, a new version of the Omnidirectional treadmill (Virtual Space Devices Inc./Army Research Laboratory) has been built, but no specifications or evaluation results have been published.

Some very creative alternative solutions have been proposed in recent years, mainly stemming from Iwata's lab. However, all of these proposals are still in the stage of preliminary prototypes, which serve more as proofs of concept than as interfaces that really allow for natural, immersive locomotion through large VEs. One prototype consists of powered shoes, which keep the user in place by means of actuated wheels in the soles of the shoes [Iwata et al. 2006]. Obviously, postural stability and effective recentering are a concern with this kind of interface. Moreover, the user can only be repositioned in one direction at any point of time. This is not true of another interface, the CirculaFloor, which consists of moving tiles [Iwata et al. 2005]. The user steps from tile to tile, while they move in order to keep him/her in approximately the same position. Although elegant, this solution does not allow for high

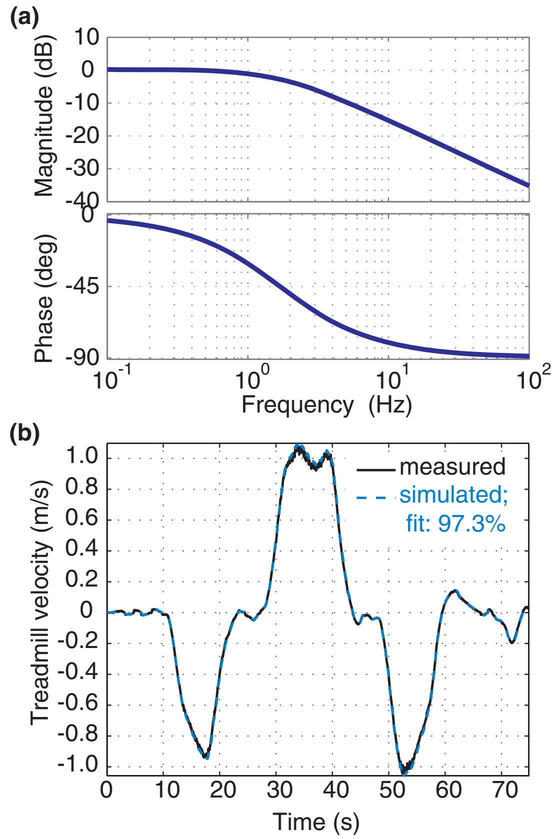

Fig. 11. System identification results. (a) Bode diagram of the identified velocity transfer function in the main chain direction. (b) Result of a model validation test for the transfer function in a.

or even normal walking speeds, and needs a complicated control system. The String walker, finally, has the user slide over a smooth surface by means of strings attached to both feet [Iwata et al. 2007]. Although this does make it possible to walk in any direction, walking speed is still very limited and the walking movements are not very natural.

2. SYSTEM CHARACTERISTICS

The low-level control framework of the platform, responsible for directly actuating the motors, is interfaced via LAN to a remote PC where the higher-level motion control algorithms are executed (Figure 10). The interface allows sending velocity commands to both motion directions and reading the actual velocity of the belts at a rate of 20Hz. The individual belts and their drives, as well as the motor drives of the main chains, are connected via a CAN bus system. A joystick interface is available to control treadmill velocity for demonstration and testing purposes.

A dynamical characterization of the treadmill was performed to assess discrepancies between commanded and measured velocities. To this end, we recorded the treadmill velocity response to sinusoidal commands (ranging from 0.05 Hz to 5 Hz), and used the *pem* function (prediction error estimate of a general linear model) of Matlab's System Identification Toolbox to fit a suitable linear model. This function must be provided with the parametric structure of the model: after trial and error, a structure with one pole and no zeros was chosen.

Model identification was performed separately for the two motion directions of the treadmill system, using separate data sets. In the lateral direction (that of the belts) the transfer function practically coincided with the identity in the range of frequencies of interest, while in the x direction (that of the main chain) we obtained

$$\frac{V_c(s)}{V_{cmd}(s)} = \frac{1.0275}{1 + 0.093967s}, \tag{1}$$

where V_c and V_{cmd} are, respectively, the measured and commanded treadmill velocities. The identified transfer function is shown in Figure 11(a).

Several further data sets have then been used for model validation (the *compare* function of the System Identification Toolbox computes the model output corresponding to a given input and compares it with the measured output). In all validation tests fits over 91% were obtained, confirming the reliability of the identified model (e.g., see Figure 11(b)). Inclusion of this identified dynamic model in the control design was found irrelevant; see De Luca et al. [2009] for details. This allowed us to neglect the treadmill dynamics and consider the commanded velocity and actual input for control design purposes.

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