Generalised Algorithms for Redirected Walking in Virtual Environments

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ABSTRACT

Several authors have identified benefits from allowing users to move through a virtual environment (VE) by walking in the real world. However implementation of this approach can be problematic, particularly for large-scale VEs, primarily because of the need to avoid the user colliding with real-world obstacles. 'Redirected walking'[1] offers a possible solution to this problem — this algorithm directs the user's movements in the real world by imperceptibly rotating their orientation in the virtual world. This paper extends the original redirected walking algorithm to increase its applicability to a wider range of VEs. Results are presented from simulations of these algorithms which provide guidance for development of an immersive virtual reality system based on redirected walking.

1. INTRODUCTION

Several researchers have reported benefits arising from the use of the whole body for user input in virtual reality (VR) systems. For example [2], [3] proposed the Body Centered Interaction paradigm, in which all user interactions with the virtual environment (VE) are via whole body gestures. The intention is to closely match proprioceptive data with that received via the other senses. The validity of this concept is supported by [4].

In particular for many tasks walking in the real world is the most natural means of moving through the VE. Research has shown that allowing the user to navigate through the VE by walking rather than by using less natural input devices such as a mouse or a glove has numerous benefits. These include improved acquisition of spatial knowledge [5] [6], superior estimation of distances [7], and an increased sense of presence [8], [9].

However the implementation of a walking interface is not straightforward. The simplest approach would be to track the user's movements in the real world and map these directly into movements of the user’s avatar (their representation within the VE). Several technologies exist for performing this tracking, such as visual/optical systems or electromagnetic trackers.

A major constraint on this approach is that all practical technologies currently available only allow tracking of the user within a limited space within the real world. Even if a tracker with effectively unlimited range was available, there would still be a need to limit the movements of the user to a finite area to avoid the possibility of collision with real world obstacles. If the user’s real-world movements are to be directly mapped into the virtual world, then the VE can be no larger than the maximum available area in the real world. Therefore the size of the trackable area defines an upper bound for the size of the VE. It is fair to assume that for reasons of cost, the range of the tracking systems and the dedicated space available will be relatively small, and so this will greatly limit the size of the VEs which can be implemented, and hence the range of applications to which this technology can be applied.

2. MAPPING SMALL REAL-WORLD SPACES TO LARGE VIRTUAL ENVIRONMENTS

Several approaches have been suggested to restrict the user to a small real-world area whilst still allowing exploration of a much larger virtual space. One possible solution would be to scale the user’s movements to correspond to larger distances in the VE. However this would lead to problems with the accuracy with which the user could control their avatar, detract from the realism of the experience and also likely detract from the benefits in terms of distance estimation reported by [7].

The most common solution has been to restrict the user to a fixed location in the real world, whilst interpreting their motions and using these to control movement within the VE. Generally this has involved the use of a physical device which measures the user’s motions whilst also constraining their location. Many different devices have been used, including treadmills and stationary bicycles [10], [11], tethers [6] an ingenious 2-dimensional treadmill [12] and roller-skates [13].

An alternative approach which doesn't require any physical device other than a tracker is the Virtual Treadmill [2]. In this system the user mimics the action of walking by performing a "walking on the spot" action. This gesture is detected by analysing the signal from a tracking device mounted on the user's head, and results in movement of the avatar within the virtual world.

All of these approaches suffer from a common problem — they no longer allow a genuine walking action on the part of the user. In some cases the user is physically constrained by the device and will always be aware of this restriction. In others the surface below the user's feet is in motion, which feels considerably different from the sensation of walking on a stationary surface and also introduces safety concerns. In addition some systems involve interpretation of the user's action, with the possibility of errors leading to user frustration.

[6] showed that at least some of the benefits of full-body input can be achieved without the user performing a true

walking action. However it is questionable whether all of the advantages of walking as an input modality are achieved. At the very least, any awareness on the part of the user of a disparity between the action required by the system and a natural walking action will interfere with the user's sense of immersion within the virtual world.

3. REDIRECTED WALKING

A potential solution to these problems is the redirected walking technique. This was first implemented and demonstrated by [1], although the basic idea dates back to the science-fiction novel "Dream Park" [14]. Redirected walking guides to the user along a particular path within the real-world by subtly rotating the user's representation within the VE. When the user's view is rotated slightly in one direction in the VE, the user will subconsciously respond by turning in the opposite direction in the real world, so as to maintain the desired heading in the VE. If the rotational velocity and acceleration are suitably low, the user will not be consciously aware of this rotation. The net effect is that by setting rotation parameters based on the user's position and orientation within the tracking space, and their position, orientation and anticipated direction of movement within the virtual world, the user can walk through a large VE without moving outside the confines of the much smaller tracking space.

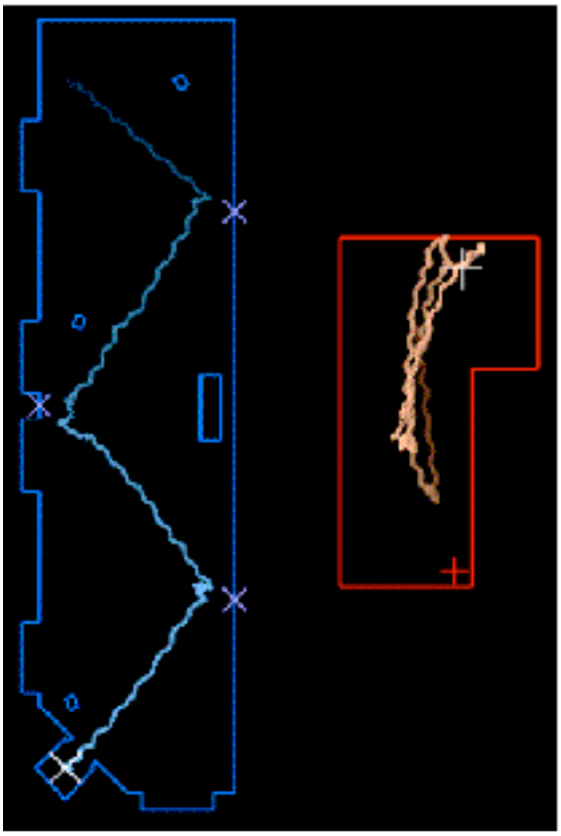

Figure 1: A user's motions within the virtual (left) and real-world (right) environments. The environments are shown at scale relative to each other.

Figure 1 (reproduced from [1]) illustrates this process. The user was required to move through the VE, pressing a series of buttons at the locations marked with crosses. These locations are referred to as waypoints. The redirected walking algorithm redirected the user to head towards the far wall of the tracking room whenever a waypoint was reached. By this means. the zig-zag path required in the VE resulted in the user following a back-and-forth path within the tracking space.

It was found that the maximum rotational velocity which could be assigned to the user's avatar in the VE without impacting on the user's conscious perception was dependent on the user's current action. A low level of rotation could be applied at any time, including when the user was standing still, meaning that introducing a need for the user to pause during execution of the task in the VE provides an opportunity to redirect them in the real world. As the user's linear velocity increased, the amount of rotation could also be increased. Finally it was possible to introduce significant amounts of additional rotation when the user was actively changing their orientation within the environment.

Whilst this study was vital in demonstrating the feasibility of redirected walking, the algorithm presented is limited, largely due to the size and shape of the tracking space. The VE and task were designed to be well suited to the use of redirected walking. In particular the use of waypoints is essential to the reported performance. The maximum distance between waypoints (8m) is shorter than the maximum straight-line distance available in the tracking space (10m). In addition the waypoints cause the user to pause and turn, which provide opportunities for the user to be redirected in the real-world. Therefore, as acknowledged by [1], this form of redirected walking is not applicable to more general VEs, where the distances traversed by the user may exceed the maximum dimension of the tracking space, and where the user's actions may not be as predictable.

4. ENHANCED REDIRECTED WALKING

4.1. GOALS

This paper aims to extend the original redirected walking algorithm to increase its applicability to a wider range of VEs. It is required that the new algorithms exhibit the following characteristics:

- restricting the movements of the user to as small an area as possible within the real-world, to minimise the cost associated with building a suitable tracking system;
- the capacity to support movement in the VE over distances greater than the dimensions of the tracking space, without the need for artificially introduced waypoints;
- the ability to perform well without explicit knowledge of the user's upcoming actions in the virtual environment, whilst retaining the ability to improve performance by exploiting such knowledge when available.

4.2. ENHANCED REDIRECTED WALKING ALGORITHMS

The main limitation of the redirected walking algorithm described in Section 3 is that the maximum straight-line distance which the user can walk within the VE is constrained to the maximum dimension of the tracking space. This occurs because the maximum rotation rate which can be applied is insufficient to completely reverse the user's heading within the tracking space before the bounds of the tracking space are reached. It is necessary to introduce waypoints which require the user to pause or turn in the virtual environment in order to provide additional opportunities for the redirected walking algorithm to reorient the user.

As pointed out by [1], this limitation could be overcome if a larger tracking space were available. This would allow the user to be directed along a circular path within the tracking space, thereby allowing a potentially infinite straight-line path to be followed in the VE. This offers a significant improvement over the original redirected walking algorithm in that it largely eliminates the need for waypoints, and therefore the existence of such a tracking space will be assumed in all algorithms proposed in this paper. Note that for reasons of space it is not possible to fully present the algorithms in this paper. Instead an overview of the key behaviour of each algorithm will be presented — for more details of the implementation see [15].

4.2.1. RETURN TO CENTRE ALGORITHM

The closer the user is to the boundary of the tracking space, the greater the risk that their subsequent actions will lead to a collision with this boundary. Therefore this algorithm redirects the user back to the centre of the tracking space. The magnitude and direction of the rotation to be applied at any point are based on a combination of the distance of the user from the centre-point, and of the angle between the user's heading and a vector from their location to the centre-point.

4.2.2. LARGE CIRCLE ALGORITHM

The return to centre algorithm makes no use of any knowledge about the nature of the virtual environment. If such knowledge is available, it may be possible to exploit so as to improve the performance of the system. The large circle algorithm aims to guide the user on a circular path orbiting the centre-point of the tracking space. As long as the user continues to move in a straight line in the VE, they can remain on this circular path in the tracking space. If a turn is anticipated within the virtual environment, then the user's location and orientation within the tracking space can be manipulated to minimise the risk of that turn resulting in a collision with the limits of the tracking space.

Figure 2 illustrates the 3 main cases addressed by this algorithm, for the situation where the user is currently on a clockwise orbit within the tracking space. In part (a) the user is approaching a right-hand turn in the virtual environment. In this case there is no need for the algorithm to take any further action, as the user's turn will be towards the interior rather than the exterior of the tracking space.

In part (b) the turn being approached is to the left, and therefore if the user remained on the current orbit then this turn will lead them towards the nearby boundary of the tracking space. In this situation the algorithm in preparation for the turn will reverse the direction of the user's orbit, as shown in Figure 2(b). In order for this action to be possible, the diameter of the circular path must be twice that of the smallest circle about which the user can be imperceptibly rotated.

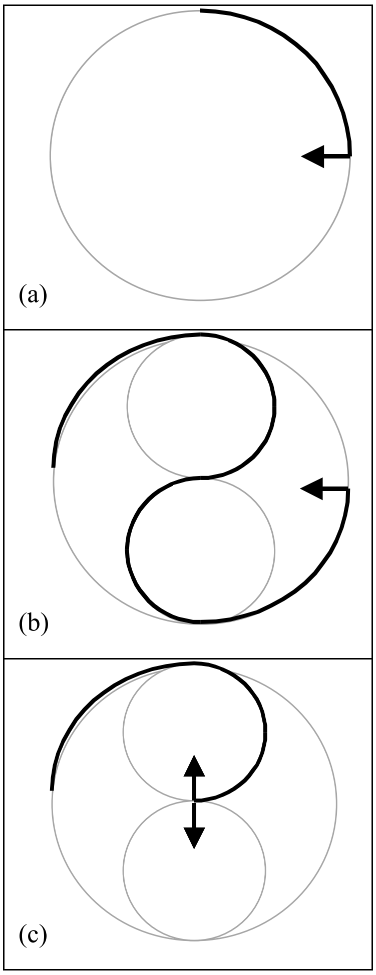

Figure 2: The paths followed by a user within the tracking space, using the large circle redirected walking algorithm.

In part (c) the distance to the next turn is known, but not the direction of the turn (for example if the user is approaching a T-junction). In this case the algorithm guides the user back to the centre of the tracking space, timing the transition so that the user reaches the centre-point in the tracking space at the same time that they reach the turn in the VE. This approach is also used in situations like those in part (b) where the distance to the next turn is insufficient to allow the complete path to the reversed orbit to be followed.

4.2.3. SMALL CIRCLE ALGORITHM

The small circle algorithm also attempts to keep the user on a circular path within the tracking space. However in this case the diameter of the circle is 1.5 times the smallest circle achievable (that in which the user is constantly rotated at the maximum non-perceivable rate of rotation. By using a smaller circle it is possible to allow the user to move outside the confines of this circle in preparation for a turn towards the interior. Conversely, by setting the target circle to be larger than the minimum possible circle, it is possible to guide the user inside the circle in preparation for a turn away from the centre of the room. These possibilities are illustrated in Figure 3. The direction of the preparatory rotation of the user, and the direction in which they are orbiting after the turn depend on the direction and the magnitude of their intended turn.

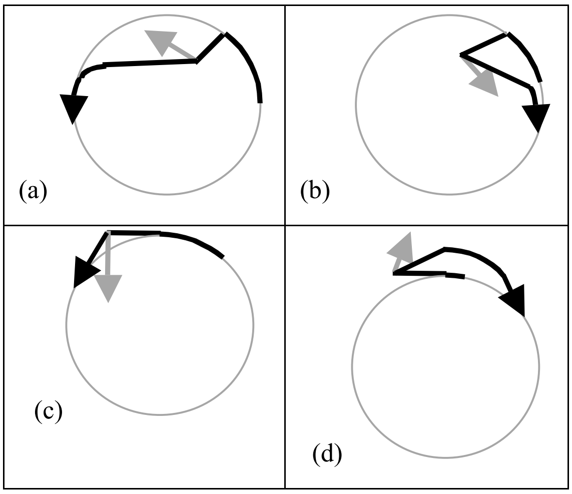

Figure 3: The paths followed by a user within the tracking space, using the small circle redirected walking algorithm.

In all cases the subsequent turn performed by the user in the virtual environment is scaled so as to guide the user back towards the target circle. For turns of less than 90° in magnitude the user's orbit will be resumed in the same direction as prior to the turn (as shown in parts (a) and (c) of Figure 3) whereas if the turn exceeds 90° it will be scaled up to reverse the direction of the orbit (as shown in parts (b) and (d).

4.3. METHODOLOGY

An immersive virtual reality system was not available for use in testing the algorithms described in the previous system. The requirements for such a system are also yet to be established, as the minimum dimensions of the tracking system necessary to allow for a circular path to be followed are not yet known.

Therefore this paper reports results obtained from simulation of such a system. This simulation allows potential issues affecting the performance of the algorithms to be identified, and the most promising algorithms selected for future implementation in an immersive VR system. These results will also provide guidance for the creation of such a system, by establishing an upper bounds on the required size of the tracking space.

The simulation models the movements of a user 'agent' within both the virtual and real environments. The agent selects a desired path to follow in the virtual environment. As the agent moves the redirected walking algorithms are applied to change their orientation within the virtual world. It is assumed that the agent will react by performing an inverse rotation within the tracking space. The agent's position within tracking space is measured over time to enable calculation of various measurements of the effectiveness of the redirected walking algorithm

The values of various parameters related to the rate of rotation have been assumed based on the results reported in [1]. Most importantly a value of 5°/second has been assumed to be the maximum rate of rotation which can be applied without the user becoming aware of this rotation. In addition, [16] reports that an intended turn of 90° by the user can be scaled up to an actual turn of up to 150°. Whilst it has not yet been tested, it is assumed in our simulation that this ratio also holds in reverse, so that this turn may also be scaled down to 54°.

Aspects of user movement such as pausing, variations in walking speed, and the rate at which the user rotates when turning would all be expected to depend on the nature of the task being carried out within the virtual environment, and to vary between individual users. Therefore these aspects were not included in the simulation — the user agents moved at a constant rate of 1 m/s, and any turns were executed instantaneously. These omissions would be expected to have a negative effect on the performance of the algorithms. In particular any pauses in the user's motion provide a valuable opportunity to reorient the user within the tracking space without changing their location — [1] reported deliberately introducing pauses into the user's motion when necessary to overcome any failures in the redirected walking algorithm. Therefore the results from this simulation should be viewed as a pessimistic estimate of the expected performance of the algorithms when applied to actual users.

Two different simulations were run. In the first test it was assumed that no knowledge of the user's upcoming actions was available, as would be the case in an open virtual environment. The agent randomly selected a location within the virtual space, turned to face that location and walked in a straight-line until the goal was reached. A new goal was then selected. This process was repeated 8 times, and the dimensions of the simulated virtual environment were 50m x 50m.

In the second simulation, on each iteration the agent selected a distance to walk, and an angle to turn (in the range -180° to 180°, relative to the current heading). This information was made available to the redirected walking algorithms. In addition on 20% of turns the direction and angle of the turn was withheld from the algorithm, to simulate the effects of turns with an unpredictable direction. Each trial of this simulation consisted of a total of 8 turns.

4.4. RESULTS

Each algorithm was tested for 10 different trials in each of the two test environments. For each trial two factors were measured - the maximum distance which the simulated user moved away from the origin of the tracking system, and the percentage of time for which the user was within the confines of the tracking system, which was assumed to be a circular region with a diameter of 60m. Tables 1 and 2 present the average, best and worst case results achieved by each algorithm across these 10 trials.

From Table 1 it can be seen that the return to centre algorithm outperformed the large circle algorithm in the simulation of a VE with no knowledge of the user's expected actions, although the performance of both algorithms was poor. Note that no results are presented for the small circle algorithm in Table 1 - this algorithm was not applicable in the case where no knowledge was available about the user's future actions.

Algorithm	Max. distance			% of time in bounds		
	Mean	Best	Worst	Mean	Best	Worst
Return to centre	24.5m	18.6m	28.8m	91.9	100.0	86.0
Large circle	28.4m	22.4m	36.1m	89.9	96.0	81.0

Table 1: Results over 10 trials of each algorithm on the simulated virtual environment with random user actions.

Algorithm	Max. distance			% of time in bounds		
	Mean	Best	Worst	Mean	Best	Worst
Return to centre	31.8m	21.6m	44.7m	85.9	98.0	60.0
Large circle	25.8m	20.4m	41.3m	92.8	100.0	74.0
Small circle	23.9m	15.3m	37.7m	92.7	100.0	71.0

Table 2: Results over 10 trials of each algorithm on the simulated virtual environment with known user actions.

Algorithm	Max. distance			% of time in bounds		
	Mean	Best	Worst	Mean	Best	Worst
Small circle	17.3m	15.1m	24.1m	99.5	100.0	95.0

Table 3: Results over 10 trials of the modified small circle algorithm on the simulated virtual environment with known user actions, whcih are restricted to right-angle turns.

Table 2 shows that by taking into account the user's expected next action, both the large and small circle algorithms were able to outperform the return to centre algorithm in the simulation where such knowledge was available. Note that the results from Tables 1 and 2 can not directly be compared as the distances between turns in the two simulations were not matched.

In observing the results from the trials summarised in Table 2, it was observed that the small circle algorithm worked particularly well for 90° turns. A further simulation was run, restricting the turns to just this angle. The results of these trials are summarised in Table 3. It can be seen that in this specialised environment the performance of this system improved considerably — the maximum distance from the centre of the tracking space was less than 20m in all trials bar one, and the user only passed outside the bounds of the tracking region on one occasion. In this case a significantly smaller tracking space (on the order of 40m x 40m) could have been used quite successfully.

5. FUTURE WORK

The next step in developing this research is to implement and test the redirected walking algorithms within a fully-immersive virtual reality system. This will enable fine-tuning of the parameters within the algorithms, by observing the maximum extent to which the user can be rotated under various circumstances before they become consciously aware of this rotation.

These practical experiments will also allow investigation of possible adverse effects of redirected walking. The issue of "simulator sickness" has been widely discussed within the VR community, and is usually attributed to mismatches between the data being provided by the body's various sensory systems [17]. Whilst [1] reported no problems with simulator sickness during their experiments, it must be confirmed that this is not an issue with the proposed extended algorithms. In addition research is required to ensure that redirected walking does not interfere with the user's acquisition of spatial knowledge about the virtual environment.

A further issue to be investigated is whether any benefits may accrue from synchronising other sensory information with the rotated visual data which is the cornerstone of redirected walking. [1] reported that the use of auditory cues which were rotated along with the visual appearance of the virtual environment appeared to be beneficial. Previous studies have shown that galvanic stimulation of the vestibular system can induce rotation of the user. It is hypothesised that aligning vestibular stimulation with the visual rotation used in redirected walking may allow increases in the maximum rotational velocity achievable, thereby further reducing the space requirements of this technique.

As indicated by the results reported in this paper, redirected walking, whilst enabling large VEs to be mapped to much smaller real-world spaces, still requires a significant amount of real-world space. One possible means of offsetting this expense would be to allow multiple users to simultaneously share the tracking space. This will require significant redesign of the redirected walking algorithms so as to avoid collisions between the users, but the potential benefits are high.

6. CONCLUSIONS

The experiments reported in this paper indicate that in a larger tracking space than that used in [1], it is possible to guide the user along a circular path and thereby allow them to walk in a straight line in the VE for extended distances. The size of the tracking space required to achieve this however is excessive. Based on our current estimated parameters the tracking space may need to be on the order of 60m x 60m. However it should be noted that these simulations did not include the capacity for rotating the user on the spot when they pause in their movements. In most applications it would be assumed the user would be required to pause to carry out some task on a regular basis, and so the space requirements would likely be considerably smaller than those suggested by these experiments.

In addition these experiments indicate that it is possible for redirected walking algorithms to exploit knowledge about the structure of the VE to reduce the required size of the tracking space. In particular the results reported for the small circle algorithm in the trial consisting only of 90° bends are promising. Whilst this constraint may appear overly restrictive, many applications may be based on corridor-like environments where such right-angled bends will dominate. This is particularly true if the VEs are designed taking into account the needs of the redirected walking algorithm, rather than being required to model existing real-world environments.

REFERENCES

[1] Razzaque, S., Kohn, Z., and Whitton, M.C., Redirected Walking in Eurographics, Manchester, UK, 2001.

[2] Slater, M., Steed, A., and Usoh, M. The Virtual Treadmill: A Naturalistic Metaphor for Navigation in Immersive Virtual Environments. In Goebel, M. (ed.), First Eurographics Workshop on Virtual Reality: 71-86, 1993.

[3] Slater, M and Usoh, M. Body centered interaction in immersive virtual environments. In Thalmann, N.M. and Thalmann, D., (eds.), Artificial Life and Virtual Reality. (New York: John Wiley and Sons): 125-148, 1994.

[4] Biocca, F. The Cyborg's Dilemma: Progressive Embodiment in Virtual Environments. Proceedings of the Second International Conference on Cognitive Technology: 12-27, 1997.

[5] Rosebrock, U. and Vamplew, P.. The Intent to Move; Generating Spatial Memory in Virtual Environments. Proceedings of the 5th International Conference on Virtual Systems and Multimedia, 1999.

[6] Rosebrock, U. The Influence of Specific Entry Devices for Navigation in Virtual Environments on the Ability to Gather Spatial Knowledge. M.Sc. Thesis, School of Computing, University of Tasmania, 2000.

[7] Iwata, H. and Matsuda, K., Haptic Walkthrough Simulator: Its Design and Application to Studies on Cognitive Map. Proceedings of the International Conference on Artificial Reality and Tele-Existence: 185-192, 1992.

[8] Slater, M., Usoh, M., Steed, A., Taking Steps: The Influence of a Walking Technique on Presence in Virtual Reality. ACM Transaction on Computer-Human Interaction, Vol. 2, No. 3 Sep. 1995, pp. 201-219, 1995.

[9] Usoh, M., K. Arthur, M. Whitton, R. Bastos, A. Steed, M. Slater, and F. Brooks. Walking > walking-in-place > flying in virtual environments. in *SIGGRAPH*. 1999.

[10] Christensen, R., Hollerbach, J.M., Xu, Y. and Meek, S., Inertial force feedback for a locomotion interface. Proceedings of the Symposium on Haptic Interfaces: 119-126, 1998.

[11] Tristano, D., Hollerbach, J.M., and Christensen, R., Slope display on a locomotion interface. Proceedings of the International Symposium on Experimental Robotics, 1999.

[12] Darken, R.P., Cockayne, W.R. and Carmein, D., The Omni-Directional Treadmill: A Locomotion Device for Virtual Worlds. Proceedings of UIST'97: 213-221, 1997.

[13] Iwata, H. and Fujii,T., Virtual Perambulator: A Novel Interface Device for Locomotion in Virtual Environments. Proceedings of VRAIS, 1996.

[14] Niven, L. and Barnes, S., Dream Park. Ace Books, New York, 1981.

[15] Field, T., Enhanced Redirected Walking Algorithms, Honours Thesis, School of Computing, University of Tasmania, 2004.

[16] http://www.cs.unc.edu/~eve/rdw/rdw.mov, Accessed 30 September 2004.

[17] Kolasinski, G., Simulator sickness in virtual environments. Technical Report 1027. Alexandria, VA: US Army Research Institute for the Behavioral and Social Sciences, 1995.