Locomotion in Immersive Virtual Environments

Manuel Kosta

Otto-von-Guericke-Universität Magdeburg
`manuel.kosta@st.ovgu.de`

Abstract. Changing the viewpoint is one of the basic interaction tasks in virtual environments (VEs). In highly immersive VEs, traditional methods, using mouse, keyboard or gamepad as input, fail to provide compelling user locomotion because they do not feel natural and are likely to cause simulator sickness. In the most natural form the user would physically walk around in the VE but this is limited to the tracking space of the setup. This literature survey therefore covers exemplary locomotion techniques for immersive VEs that are viewed through a head mounted display. We review them in the context of a framework for classification, design and evaluation of such techniques introduced by Bowman et al. In the end we will summarize the conclusions of the existing research and point out room for future work.

1 Introduction

Immersive virtual environments (VEs) have the capability to make users feel present in computer generated three-dimensional content. Therefore this technology is also referred as *virtual reality* (VR). The feeling of presence in VR is useful in a large variety of applications including: games, education, training simulators, production- and architecture-planning and marketing. The high degree of immersion is achieved by stimulating the user's senses by solely virtual cues and thus replacing cues coming from the real world. Ideally all senses would be stimulated by virtual cues but current VR technology is not capable of doing that. Thus it focuses on visual cues, since humans perceive their environment primarily through the visual sense. Sometimes audio and tactile cues are added as well, to further increase the feeling of presence.

There are mainly two different technologies to present the virtual visual cues in an immersive form, occupying nearly the user's complete field of view and responding to her head movements. On the one hand there are large screen displays surrounding the user, like CAVEs [7] or virtual workbenches. On the other hand there are head mounted displays (HMDs) which are directly attached to the user's face and completely block out visual cues from the real world. We limit the scope of this survey to locomotion techniques applicable for HMDs because these are broadly available and inexpensive compared to surround screen displays. Additionally, surround screen displays often omit the screen behind the user to simplify construction. This limits the user's possibility to look around in the VE by physical turning, whereas HMDs allow the full 360°.

Regardless of the used display technology, users must be able to change their viewpoint of the scene to get a better understanding of it or to simply explore it. The task of viewpoint movement is also referred as *travel* [3] in the literature or *locomotion* [14] when the VE is experienced from a first person viewpoint. HMDs provide rotational and often also translational head tracking so the user's head movements can be directly mapped to the virtual viewpoint, allowing the most natural way of locomotion by physical walking. However, this might not be desired in applications where large distances need to be traveled. Furthermore the space observed by the tracking-system is limited, thus for larger or potentially infinite virtual environments other mechanisms for controlling the virtual viewpoint are required. This survey will address exactly these techniques.

2 Design and Evaluation of Locomotion Techniques

What are the building blocks of locomotion techniques? What are the challenges in designing them? How can we measure their performance and compare different techniques with each other? We answer these questions in this section by presenting a general framework for design and evaluation for locomotion techniques that was introduced by Bowman et al. [3, 4, 2]. Furthermore, this section briefly introduces the causes of visually induced motion sickness which is one of the major challenges in any application of an immersive VE.

2.1 Framework of Bowman and Colleagues

Bowman et al. [3, 4, 2] present a framework for the design and evaluation of locomotion techniques. It includes taxonomies describing the design space, general quality criteria which should be used for evaluation and outside factors that might influence the performance of users with any locomotion technique. Other authors rarely refer to this framework explicitly but often use parts of it implicitly to introduce new locomotion techniques, as can be seen in section 3.

One of the taxonomies introduced by Bowman et al. divides a locomotion technique into subtasks that have to be done (see figure 1 on the next page). First, the new position must be specified where the user will move next. Also the velocity and acceleration of the movement need to be known. Different approaches include for example continuous position specification with constant acceleration and velocity or discrete target position specification with user controlled velocity. Second, the new orientation needs to be specified. Since this survey focuses on techniques for HMDs with head tracking, the users physical head orientation will mostly be used for that but different approaches are possible. Lastly, the locomotion technique must provide some user interface to start and stop the movement. By exchanging the methods fulfilling each of these subtasks, different locomotion techniques can be designed.

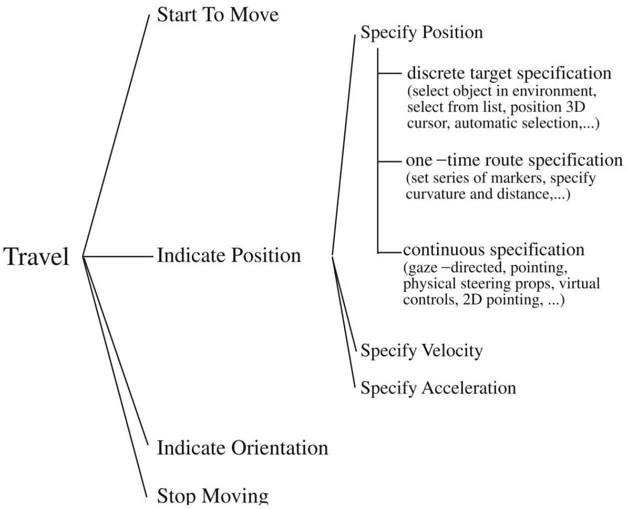

Fig. 1. Taxonomy of locomotion techniques based on the involved subtasks introduced by Bowman et al. [2, p. 620]. Only for position specification implementation categories are shown to maintain readability.

This is not the only true taxonomy but it gives a detailed view on the design space of locomotion techniques. Other taxonomies have a different viewpoints on the same design space, e.g. dividing the techniques into physical and nonphysical ones. For further information on other taxonomies see [5].

To evaluate the performance of a particular locomotion technique Bowman et al. [4] also give a list of quality criteria that can be measured in a user study. Dependent on the application, the individual importance of each criteria might strongly vary. So application designers can use these measurements to choose the appropriate technique for their application. However, the authors do not guarantee completeness of their following list:

- speed (time a user needs to complete a task)
- accuracy (proximity to the desired target destination)
- spatial awareness (the user's knowledge of his position and orientation within the environment during and after travel)
- ease of learning (the ability of a novice user to use the technique)
- ease of use (the complexity or cognitive load of the technique from the user's point of view)
- information gathering (the user's ability to actively obtain information from the environment during travel)
- presence (the user's sense of immersion or 'being within' the environment due to travel)
- user comfort (lack of simulator sickness, dizziness, or nausea)

Criteria like speed and accuracy are objectively measurable. Other ones are rather subjective and therefore difficult to measure but some stan-

dardized questionnaires do exist for *ease of use*, *presence* and *user comfort* [12]. User comfort will be discussed in more detail in section 2.2, since this is a major problem in any immersive VE.
Not only the locomotion technique affects these quality criteria but also outside factors that Bowman et al. divided into four categories: *task-, environment-, user-* and *system characteristics*. Task characteristics include the complexity of the path to be traveled or the visibility of the target location. Environment characteristics include the complexity of the environment, i.e. the number of obstacles or distracters, presence or absence of moving objects, etc. User characteristics include personal properties of a particular user like age, gender, height, reach, technical background and other. System characteristics describe the technical setup of the VE including for example the frame rate, latency, field of view and so on. When designing experiments for user studies it is important to be aware of these factors and choose their values wisely to match the goal of the experiment.

2.2 Visually Induced Motion Sickness

In this subsection we give a brief overview of the phenomenon of visually induced motion sickness (VIMS), in different contexts also referred as simulator-, cyber- or gaming sickness [13]. Depending on the content of immersive VEs, users can show symptoms like pallor, cold sweating, drowsiness, dizziness, fatigue, oculomotor disturbances, nausea and vomiting [8, 13]. These symptoms are similar to regular motion sickness, sometimes experienced in the backseat of a car or as seasickness aboard a ship. There are several theories about the causes of motion sickness. The most commonly accepted one describes motion sickness as a result of a conflict between the visual and vestibular senses [16]. Different from regular motion sickness, where the human is experiencing motion via the vestibular sense but not the visual one, visually induced motion sickness is caused the other way around. The visual sense experiences motion but not the vestibular one. The visually induced, illusory sensation of motion is called *vection*. Keshavarz et al. [13] review the research done on VIMS and conclude that vection might be a necessary but no sufficient prerequisite for VIMS, so the experience of vection alone does not directly imply VIMS. This is good news for the design of locomotion techniques, since the change of the virtual viewpoint in an immersive VE is likely to induce vection and sometimes even designed to do so to increase the feeling of presence.

3 Review of Locomotion Techniques

After having discussed the issues regarding design and evaluation of locomotion techniques, in this section we will give a literature review of some exemplary implementations that were evaluated by an user study. We do not claim this review to cover all existing techniques because the design space is huge and not all proposed techniques are thoroughly evaluated in a user study. For a broader overview, refer to [17, 5, 19].

Many techniques have been proposed that require specialized hardware like treadmills, pressure sensitive boards, and full body tracker (an overview can be seen in [11]). Since those devices are often unique prototypes, we will not cover them in this survey and instead focus on techniques applicable for HMDs with positional head tracking and gamepads or motion controllers with 6 degrees of freedom (DoF) as input devices because this hardware is broadly available. We divide the techniques, according to the taxonomy of Bowman et al. (figure 1), by their method of position specification into the categories continuous and one-time-route specification. We subsume the discrete target specification under the one-time-route specification because it is basically a subcategory, where the route consists of one waypoint only.

3.1 Continuous Specification

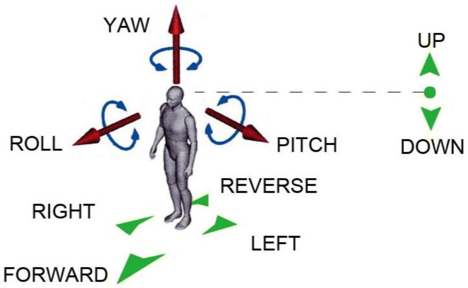

Fig. 2. Illustration of the head controlled 6 DoF locomotion technique presented by Chen et al. [6, p. 112]

Locomotion techniques using this type of position specification continuously update the user's desired target position – or rather the desired movement direction – so the user can change her movement direction at any point in time.

Chen et al. [6] present a head controlled approach in which the user starts in a calibrated neutral pose (position and orientation) where no movement is applied to the virtual viewpoint. When the user leaves the neutral position the vector between the new and the neutral position is used to continuously translate the virtual viewpoint in that direction until the user comes back to the neutral position (see figure 2). The distance to the neutral position is mapped to the velocity of the virtual movement. Since this technique is presented for a CAVE, same holds for rotation, to compensate the rotational limits imposed by missing walls. So when the user turns her head out of the neutral orientation the virtual viewpoint continuously turns in the same direction until the user turns her head back to the neutral orientation. When used in an HMD one could possibly omit the yaw control and directly use the user's head rotation around the vertical axis. Pitch and roll however, need to be retained because, other than yaw, humans cannot rotate easily the full 360° along these axes. Chen et al. compared this technique against gamepad locomotion which had the same controls mapped to thumb sticks and buttons instead of body movements. In a user study they investigated the effects of the chosen locomotion technique on the severity of simulator sickness symptoms, level of presence and user performance in a three dimensional slalom task. Their results show that subjects were faster using the head controlled locomotion and had overall better control which indicates that controlling 6 DoF simultaneously is easier when full body movement can be used. Additionally, severity of simulator sickness symptoms were slightly lower and presence slightly better using the head controlled locomotion. Chen et al. ascribe this to the physical motion in this technique which might reduce the conflict between vestibular and visual senses.

The concept of continuous specification of the movement direction is also called *steering*. Bowman et al. [4] compared gaze-, torso- and pointing directed steering techniques where the movement could be initiated and stopped by pressing a button and the movement speed was held constant. They hypothesized that torso steering and pointing are better suited for an information gathering task because these techniques allow looking around while moving in a different direction but at the same time require more cognitive load, thus possibly diminishing the look-around-advantage. In their user study they did not find a significant difference in the information gathering performance among the compared techniques. They noted however, their subjects often imitated gaze-directed steering when using the other two techniques therefore possibly diminishing differences in measured performance.

Natural walking uses continuous position specification too by directly mapping the user's head position to the virtual viewpoint. But the possible movement distance is limited by the physically available space and the used tracking system. To overcome these limits, techniques have been developed that scale the user's physical translational movements to cover larger distances in the VE [20, 10]. However, scaling up the user's movements consequently reduces the accuracy of her virtual movements. Additionally, it is crucial to scale the movement only in the direction the user intended to move in. E.g. amplifying side to side or up and down head movements, that are natural to human walking, should be avoided. Nevertheless, a user study carried out by Williams et al. [20] indicated that scaled walking performs better than gamepad locomotion on a spatial awareness task.

Related to scaled walking is the method of *redirected walking*, introduced by Razzaque et al. [15]. This technique exploits the human's inability to detect small discrepancies between visual and proprioceptive sensory input. The user is walking naturally in the VE but her virtual viewpoint is imperceptibly manipulated so that she physically walks along a path that lies inside the limited tracking area while she perceives a path that exceeds these boundaries. The viewpoint is rotated around the vertical axis centered at the user's head whenever the user is likely not to detect these rotations, e.g. when she is walking or turning. Steinicke et al. [18] investigated on perceptual thresholds for these redirections and found that users, visually following a straight path and focusing on detecting visual proprioceptive discrepancies, can be redirected onto an arched physical path with a radius of 22m or more without their notice. Hodgson et al. [9] show that redirected walking does not affect the user's spatial awareness in the VE, thus the performance of redirected walking is as close to natural walking as possible while requiring less space. Nevertheless, with 44m in diameter the required space is still huge. Although users, distracted by other tasks than locomotion, can unnoticeably be redirected onto an arched path with a smaller radius of 11m [9], the required space remains too large for most applications of immersive VEs. Additionally existing implementations are tailored to the specific content of a VE. Arbitrarily applicable algorithms have not been developed yet.

3.2 One-Time-Route Specification

These techniques allow users to specify a path they want to move along before the actual viewpoint movement is performed. In the simplest case this route consist of only one waypoint, which represents the subcategory of discrete target specification. Once the movement is initiated, the computer takes control over the virtual viewpoint and the user has no other controls – if any – than to stop or continue movement.

One example for a technique using discrete target selection is presented by Bolte et al. [1]. Their so called "jumper metaphor“ lets the user define her next target position by her gaze. When she looks for a certain amount of time in approximately the same direction, the nearest surface point in this direction is selected as the new target position. To move there, the user needs to accelerate her head in the direction of the target, exceeding a certain activation threshold. Then the system moves the viewpoint on a linear path with a predefined speed, adding smooth acceleration and deceleration phases at the beginning and end of motion as well as some motion blur. To evaluate their proposed technique, Bolte et al. performed a small user study with 11 subjects performing a move-to-target-task, comparing the jumper metaphor with real walking and simple teleportation, which is basically the same as the jumper metaphor without movement animation. Results show that there are no significant speed differences using either approach. However, users judged the jumper metaphor slightly harder to learn but more effective than real walking. Teleportation was experienced as significantly less satisfying compared to the other two techniques and also significantly decreased the subjects' spatial awareness as also found by a study of Bowman et al. [3], showing that smooth viewpoint transitions are preferable when spatial awareness is important.

Pausch et al. [14] present a 3D miniature map to the user, representing the virtual environment surrounding her, in which she can define her next target position. A doll indicates the user's current position and orientation. She can manipulate the pose of the doll in the miniature whereupon the virtual viewpoint of the surrounding environment updates accordingly. Since an abrupt change of the viewpoint is expected to be disorienting the computer generates a fly animation into the miniature to transform the viewpoint gradually to the new location. There is no formal user study evaluating this concept but the authors state, during informal user observations users found the technique easy to use. When comparing this concept to other techniques we have presented so far, one might consider the need for an additional manipulation technique (namely moving the doll) a disadvantage of this approach because the user might be distracted from their actual task in the VE.

Bowman et al. [2] used also a miniature model of the environment to specify a movement path through the VE. They compare it against a steering-by-pointing technique and a fully automatic technique on their ability to maintain the user's spatial awareness. The automatic technique gives full viewpoint control to the computer. By pressing a button the user can only start and stop the movement. The technique using the miniature let the user specify a path through the environment by placing waypoints in it. The computer then generates a path by linearly interpolating these way points. Once the user completes the path specification, she can start and stop the movement with the press of a button. All these techniques use constant speed. In a user study the subjects traversed a corridor with multiple turns and 3 different objects placed somewhere in it. The task was to traverse the corridor, memorize each object's position and when reaching the corridor's end, blindly point at a specific object, seen in the corridor (objects and corridor were hidden). The angular difference between the user's pointing and the actual object position served as an indicator for the spatial awareness the user had while traversing the corridor. Results showed no significant, direct effect of locomotion techniques on the spatial awareness. However, some subjects exploited the possibility of the pointing technique to travel freely in 3D space and develop sophisticated strategies to memorize the objects' positions; for example moving up high to get a 3D overview. These subjects had better scores on the pointing tasks.

4 Summary and Conclusion

In this survey we have seen an useful framework for designing and evaluating locomotion techniques for immersive virtual environments that includes taxonomies which structure the design space and a list of quality criteria that allow a more general applicable evaluation [4]. In this context we briefly covered the causes of simulator sickness and how these influence the design of locomotion interfaces. As an example for that, we have seen the teleportation technique which is designed for minimizing vection to reduce simulator sickness but sacrifices spatial awareness. Furthermore, the study of Bowman et al. [2] indicates that user performance can be increased by granting the user as much control as possible, provided she is able to realize and use the full potential of these controls. So techniques using continuous position specification might be preferable for applications frequently used by their users because their performance will significantly increase once they get used to the technique.

Unfortunately there exists no defined standard for the evaluation of locomotion techniques which makes meaningful comparison of different techniques difficult. The presented framework provides useful guidelines but is not detailed enough to be used as a standard. Additionally, it seems unrealistic to perform tedious measurements for every quality criterion if the authors are interested only in a small portion of them. Here exists room for further research. Especially studies explicitly investigating the effects of locomotion techniques on the occurrence of simulator sickness are rare.

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