Developing Effective Navigation Techniques in Virtual 3D Environments

Sabine Volbracht and Gitta Domik

Computer Graphics, Visualization and Image Processing
University of Paderborn, Fürstenallee 11, D-33095 Paderborn
sabaro@upb.de, domik@upb.de

Abstract. As a result of the increasing use of three-dimensional environments and of frequently inefficient possibilities for navigation, a fundamental understanding of navigation is becoming ever more important, both for users as well as for developers of three-dimensional environments. To promote this understanding a rigorous model for navigation was developed. The navigation model contains the relevant factors of influence and determines quality criteria for an efficient navigation. The model is used in a practical study. In this study effective navigation techniques in the application field of teaching/learning environments for children of elementary schools are implemented and evaluated. The simple control of relevant parameters, made possible by the model, can be transferred easily to other ranges of application.

1 Introduction

3D environments account already for a large portion of user interfaces in e.g. World Wide Web, game industry, architecture, tourism industry as well as within the scientific area with visualization and simulation. However in many cases existing virtual 3D environments indicate a lack of usability, which can be attributed to non-intuitive and misleading navigational techniques. Non-intuitive and/or misleading navigation techniques do not only cause frustration but also provoke unrecoverable errors of the user. Therefore the development of efficient navigation concepts for virtual 3D environments becomes more important.

2 Definitions of Navigation and Wayfinding in Virtual Environments

Darken and Sibert [7] define the term navigation e.g. as "… the process by which people control their movement using environmental cues and artificial aids such as maps so that they can achieve their goal without getting lost." Elvins [10] defines the term more generally:"Navigating is most often defined as the process of following a course by making directed movements, … ." Closely connected to the process of navigation is the process of wayfinding. Elvins [10] defines this process as "… determining the strategy, direction and course needed to reach a desired destination." The difference between these two procedures explains Elvins [10] as follows: "Without wayfinding, a navigator won't know in which direction to steer and without navigating, a wayfinder will not have the means to move toward their destination." So we understand navigation in virtual environments as: "the process of determining a strategy, direction and course (wayfinding) with controlling the movement using some aids to achieve a desired goal".

The third important term associated with navigation and wayfinding is 'spatial orientation'. Maier [17] defines this term as "the ability to physically and mentally find one's way in two- and three-dimensional space". This ability is important for an effective navigation and wayfinding, because an effective navigation involves good orientation, that means e.g. to know where to be, to know where to go and to know where to come from.

3 Related work

Bowman and Hodges [2] developed a methodology for the improvement of the usability of interactively complex VE applications. Concerning navigation they limited their methodology to immersive environments and to the pure movement ('travel') through an environment. The results of a workshop organized from Jul and Furnas [13] give general overview of different issues in navigation in electronic information environments such as different definitions of navigation and related concepts, aspects of psychology and other factors influencing navigation. Furthermore a number of researchers have studied individual aspects of navigation and wayfinding in virtual environments. In their efforts individual factors influencing navigation were classified and/or examined but dependence on other factors was often not pointed out. Darken and Sibert [7] developed a classification of virtual environments with three attributes: Size: (small, large, infinite), density (sparse, dense, cluttered), and activity (static, dynamic). For defining the scope of her work about designing virtual environments for usability Kaur [14] divided VEs into single/multi-user environments, in 'real world models'/'abstract models', and in 'immersive'/'augmented'/'projected'/'desktop' environments. Different investigations in immersive virtual environments for the study of human navigation behavior and human perception [11][23] exist. These efforts give insight into navigation strategies used in VEs. Krieg-Brueckner et al. [15] developed a taxonomy of navigation behavior for an autonomous wheelchair. This taxonomy is also helpful for classification of navigation strategies for virtual environments. Darken and Sibert [7] investigated the effectiveness of different navigation aids e.g. landmarks, coordinate output, maps etc. in a large, sparse world (ocean with ships). In additional studies they examined navigation behavior of users with different navigation aids to develop design principles for immersive, virtual environments [4] [6]. Satalich [19] examined the effect of 2D-maps as navigation aid under different conditions. Special navigation aids were developed e.g. by Pausch et al. [18], a 3D-map (World in Miniature) for buildings, and interactive 3D-Bookmarks (3D-Thumbnails) for virtual cities by Elvins et al.[9].

Many approaches related to interaction/motion techniques' exist as part of the motion control in a VE. Ware et al. [26] defined motion metaphors like 'flying', 'eyeball in hand' and 'scene in hand'. Hinckley et al. [12] defined another metaphor, 'ray casting', by which "the user indicates a target by casting a ray or cone into the 3D scene". A further motion metaphor is 'world in miniature' from Pausch et al. [18] and Stoakley

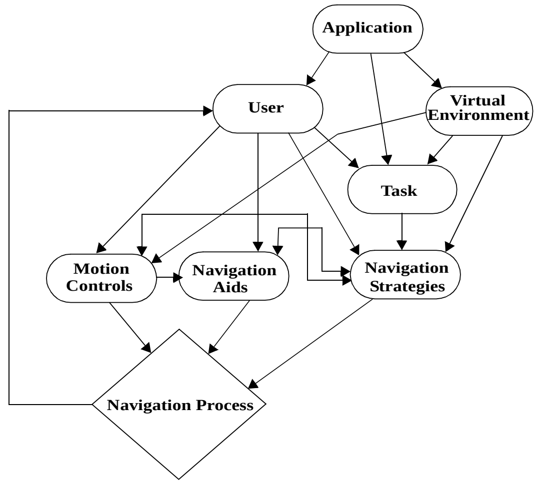

Fig. 1. Model of Navigation

et al. [20], by which the user makes movements on a 3D-map, which will then transfer to the virtual environment. Mackinlay et al. [16], developed the method 'logarithmic flight' for fast and controlled movement in 3D environments. Bowman et et al. [3] developed a formal approach for categorization of motion techniques, a taxonomy of 'travel' techniques in immersive environments. Strommen [22] compared three mouse-based interfaces for children to control virtual travel in a non-immersive video-based environment. The following model developed by the authors is based on the current understanding of navigation and wayfinding.

4 Model of Navigation

The model presented here defines factors of influence and their interdependencies for navigation techniques in virtual 3D environments (Figure 1). The model is used to classify each factor with consideration of their interdependencies and characterizes a navigation technique as an intersection of sensible staging of parameters. Therefore the use of the model supports design of new and selection of existing navigation techniques, as well as evaluation and comparison of different techniques.

4.1 Description of Factors influencing Navigation in Virtual Environments

In the last few years, different individual aspects of navigation in virtual environments have been considered. To summarize this work, whilst at the same time taking into account the work of Jul and Furnas [13], as well as Domik and Gutkauf [8], in the field of visualization, it has been shown that effective navigation in a virtual 3D environment within an application area depends on a combination of characteristics stemming from the following six factors: environment, user, task, navigation strategy, navigation aid, and motion control.

Examples of *application* areas using virtual environments (VEs) are e.g., arts and entertainment, marketing, teleoperations, telepresence or collaborative VEs, prototyping, education, training, treatment (e.g. of phobia [21]) and scientific visualization. Factors influencing the quality of navigation in virtual environments can be explained as follows: The factor *environment* describes structure and different attributes of VEs like display mode, topic, degree of abstraction for representation, size, density, activity and single-/multi-user environment. The choice of the virtual environment and the design of the environment with all of its attributes depends only on the application itself. The design of the environment may depend indirectly on the navigation aids and, to be more specific, if the user desires particular navigation aids which have to be integrated in the environment. The factor *user* defines the characteristics of the user (age, gender), as well as the abilities and weaknesses of a user. The user group is determined by the application, which fixes the general, application-oriented characteristics of the users. Application-oriented and individual characteristics of the users influence the choice of the task or goal, the user pursues in a virtual environment, and the navigation strategies, which are necessary for performing the task or for reaching the goal. Likewise they influence the selection and the design of the navigation aids and the motion control. The *task* defines the problem a user would like to solve in the environment. For solving a problem in VEs different navigation tasks must be performed, e.g. target search, exploration, etc. For an effective navigation technique in a VE, the task to be performed in the environment has to be selected in accordance with the application and the environment. For example, in designing the presentation of the tasks, additional user information has to be included. *Navigation strategies* describe concepts people use to navigate through an environment. Navigation strategies are complex strategies which consist of elementary navigational tactics like 'searching', 'vectorial navigation' and 'positional navigation' [15]. These in turn consist of basic actions (i.e. 'reaching target', 'course following' or 'wall following' [15].). The selection of the navigation strategy depends on the user, on the environment and on the task. Users can prefer particular strategies. If these preferred strategies are not supported, as for example through the supply of corresponding navigation aids, then the user must first become accustomed with those aids which can impair the effectiveness of navigation. However, not all strategies are sensible in a defined environment. Consequently, the parameters for the environment also determine the choice of strategy. *Navigation aids* are aids for determining direction and/or position. They can be both part of the environment (like landmarks, sound or signs) as well as also consisting of external objects (maps or compass). Navigation aids support orientation in space and therefore serve the purpose of finding the way. They include: a) aids which exclusively serve the function of determining position (maps showing actual position, coordinates or identification signs); b) aids which exclusively serve the function of determining direction (compass, directional signs); and c) aids which are a combinations of both (reassurance signs, sounds or markers). Navigation aids depend directly on the strategy selected, as the aid is implicitly included in the strategy. *Motion controls* are the hard- and software components for moving through a VE. Motion control is further differentiated into input device, motion aids (e.g. cursor, direction buttons, avatars etc.) and interaction/motion technique. The interaction/motion technique defines motion metaphors like 'walk', 'fly', or 'jump' and different parameters of movement such as direction/target selection, velocity/acceleration selection and input condition [3]. The last parameter, motion control, specifies pure movement through a virtual environment. The choice and the design of motion control depends very substantially on the user and the navigation strategy, as well as the environment. In this context, the motor skills of the user, for example, are of particular importance. The navigation strategy can also influence the pure movement in an environment. The strategy of 'automatic path following' presumes that the user himself/herself does not control the movement, but that s/he is being 'transported' and so hands over control to the system. The display mode of a VE particularly influences the motion control. For example, immersive environments demand other input devices and motion metaphors than desktop environments. Table 1 summarizes factors influencing the quality of navigation and shows example characteristics.

Table 1. Factors influencing navigation and their example characteristics

Factor	Example Characteristics
Virtual Environment	Display Mode: immersive VE, desktop VE, projected VE, augmented VE • Topic: city, building, landscape, sea etc., information visualization • Degree of abstraction for representation: very realistic up to abstract • Size: small, large, infinite • Density: sparse, dense, cluttered • Activity: static, dynamic • single-/multi-user environment
User	Characteristics: age, gender • Knowledge about: currently perceivable sub-section of the environment, current environment model, application task, application domain, real world and other environments [14] • Experiences in: use of computer, 3D environments • Abilities: motor, perceptual • Disabilities: motor, perceptual • Expectations
Task	Problem with primary and secondary navigation task: Primary navigation task: movement with wayfinding, that means searching (e.g. exploration, naive search, primed search [5]) • Secondary navigation task: application tasks with movement and wayfinding as secondary process
Navigation Strategy	Navigation using specific aids • Search strategies [5]: edge following search method, lawnmover search method, heuristic search method, area search method
Navigation Aids	Orientation: compass, directional signs • Position: maps showing actual position, coordinates, Identification signs • Combination: reassurance signs, sounds, markers
Motion Control	Input devices: keyboard, 2D/3D-mouse, joystick, spaceball • Motion aids: direction buttons, cursor, avatars • Interaction techniques: Motion metaphors: walk, fly, jump, teleport • Direction/Target Selection: gaze-directed steering, pointing/gesture steering, discrete selection (lists, environmental target) [3] • Velocity/Acceleration Selection: constant velocity/acceleration, explicit selection (discrete, continuous), user/environment scaling, automatic/adaptive [3] • Input Condition: constant movement/no input, continuous input, start and stop input, automatic start or stop [3]

4.2 Criteria of quality

For an effective navigation, it is important for the user to be able to orient himself in space and build up landmarks, survey and route knowledge, in order to be able to create a cognitive map of the virtual environment. In addition, movement through a virtual environment must take place secondarily, so that the primary task can be processed without restriction. Effective navigation is consequently a fast and direct navigational process, which supports the application underlying it and which takes into consideration the attributes of the environment which have been modeled. The process should offer to the user his/her preferred navigational strategy and make available to him the corresponding navigation aids and movement controls. In order to guarantee this for an area of application, it is important for the selection or development of an effective navigational procedure to select a sensible selection of parameters, depending on the factors listed above.

An effective navigation technique is dependent on many factors of influence. Apart from the quantitatively measurable sizes like ’task completion time and ’accuracy of reaching the goal’ the following qualitative measurements are important: ’Easy to use’ as well as ’easy to learn’ (directed mainly at the navigation aids and motion control), ’spatial orientation’ and ’satisfaction of the user’.

5 ’City Game’ - A practical application

’City Game’ is an interdisciplinary project of a research group specializing in didactics of mathematics (Backe-Neuwald and Rinkens) and a computer science group (the authors of the paper) at the University of Paderborn [25]. The aim of this interdisciplinary project was the development of a computer-supported teaching/learning environment oriented to the future and, in detail, a virtual 3D-city for children of elementary school (grade three to four) for performing tasks deriving from the subject area of spatial orientation. Spatial Orientation is an important ability that is taught in various lessons at German elementary schools. At the same time, orientation in a city is a theme which is very frequently used, because it has great relevance to the circumstances in which the children find themselves. In this project, the tasks forming the content of the work were from the area of mathematical didactics, while the conceptual tasks - such as modelling, preparing animations and the development of interactive and navigation techniques-come from the domain of computer science. The environment was developed with the modeling language VRML 2. 0 (Virtual Reality Modeling Language). Thus the environment is characterized as ’Desktop VE’. The city consists of a realistic structure and typical buildings and items. Various navigation aids for orientation are offered to the user, e.g. a 2D-map, which shows the actual position of the user in the city, and optionally displays the path covered so far, road signs, a hard-copy of the city map, and a wind rose for orientation with the four directions of the compass. Therefore different real-world navigation strategies are supported. Motion control is performed interactively by a standard mouse and direction buttons (forward, backward, left and right) using the ’walk’-methaphor and constant velocity.

6 Evaluation of Navigation in the 'City Game'

The 'City Game' was subject of different investigations to serve the purpose of developing effective navigation techniques for children by using the model. For gathering relevant data about navigation behavior and user characteristics for this application two informal studies were conducted by using the following qualitative evaluation techniques: 'thinking aloud', 'observation' and 'interview'. The results of these studies were mapped into the factors of our model. Currently, we are developing formal studies, based on experiences of previous experiments within the area of 3D-perception [24], which examine different independent variables derived from results of the qualitative studies. The dependent variables are 'time' ('total time' and 'time at decision points') and 'accuracy' ('total distance' and 'deviations from the actual way') for quantitative comparisons and empirical evaluations.

The focus of the first informal study was a comparison of navigation behavior between children and adults in a virtual environment [1]. The study included ten children (grade four) of an elementary school and ten students of the University of Paderborn. In this study subjects had to find their way from different initial positions to different target positions (navigation tasks). Each trial should be performed with a different navigation strategy with different navigation aid, e.g. navigation with the city map, with photos along the way to be found, with the wind rose or by navigation without external aids. Before beginning the study each subject was shown a walk through the city and taught the use of the direction buttons. The subjects were asked 'to think aloud' during performing their tasks. The comments were recorded by video and in written notes by the evaluator. The results indicate that children and adults use different objects for orientation dependent on subjective perception and experience in daily life. Further, it could be observed that children and adults have different priority by using navigation strategies and navigation aids. Another important result was that subjects (both children and adults) often focused on the motion control (standard-mouse and direction buttons) rather than on their tasks.

To find out preferred navigation strategies of children and to compare their navigation behavior in real and virtual environment a second informal study was conducted [1]. In this study, forty-two children (from two classes of grade four) of an elementary school participated. Both in a virtual as well as in the real environment the children had to remember a route along which they had proceeded and find their way back. The main results of this study were: The children remembered the route on the basis of specific landmarks which differ dependent on the environment. In the virtual environment, locations and objects were noticed by the children which appeared to be real and which have a strong link to the realities of the children's lives. In the real environment locations were remembered which were linked to events (meetings with humans and animals) and which deviated from an ideal, typical condition (e.g., a broken window). It could further be observed that children developed a superior understanding of the overall scene while they were in the real environment rather than in the virtual environment and that children wanted to transfer their experiences from the real environment to the navigational process in the virtual environment. All these results verify the importance of each factor and show the different interdependencies.

An important result for further formal studies is that preferred strategies of children in the real environment are 'orientation through events' and 'ask people'. This resulted in two additional characteristics for factor 'navigation strategy' ('navigation using dynamic landmarks', 'navigation using interactive landmarks') and for factor 'environment' (static/dynamic). Whether these strategies can be used successfully in the virtual environment still needs to be evaluated.

An additional, important result of the preliminary study was that children had difficulties in gaining an overview over the virtual environment. It is generally known that a 2D-map is a powerful aid for gaining an overview. Children of elementary schools must, however, first learn how to work with a 2D-map. Consequently one suspects that a 3D-map, whereby the transfer from 2D to 3D and conversely does not have to take place, may result in children acquiring an overview in virtual environments. Therefore we included 3D-maps as additional characteristics for the factor 'navigation aid'. Another addition was made to the characteristics of the factor 'motion control': keyboard and joystick should be tested as alternatives to the mouse to overcome previous problems with the motion control. An overview of controlled and varied characteristics of factors can be found in Table 2. The content of this table serves as part for a formal evaluation of varied characteristics.

7 Summary

We have developed a rigorous model describing navigation and its influencing factors: environment, user, task, navigation strategy, navigation aids, and motion control. To validate this model and its use for creating and evaluating navigation techniques in a virtual 3D environment, we used the 'City Game'. In a first series of qualitative studies we observed children and adults in different navigation situations. We then mapped the results of this studies into the factors of our model to check its usefulness, which we could verify. We then used the model and results of the first studies to set up further formal studies to evaluate formally various characteristics of factors in the 'City Game'.

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Table 2. Controlled and varied characteristics for further empirical studies

Factor	Characteristics - controlled	Characteristics - varied
Application	Educational environment for geometry course in elementary school (grade three and four) ● Topic: ’Orientation in space’ ● Subtopic: ’Orientation in the city’	
Virtual Environment	Display Mode: desktop VE ● Topic: ’city’ ● Degree of abstraction for representation: very realistic ● Size: large ● Density: dense, but some sparse places ● single-User Environment	Activity: static/dynamic landmarks
User		Children / adults Children (grade three and four) of elementary school ● low experience in the use of computer ● low experience in navigation and wayfinding tasks in real and virtual environments Adults● high experience in the use of computer ● high experience in navigation and wayfinding tasks in real and virtual environments
Task	Navigation-/Wayfinding tasks Navigation as primary task Representation of the tasks: verbally	
Navigation Strategy		navigation using landmarks: a) static/dynamic ● b) interactive/non interactive navigation using maps
Navigation Aids	global landmarks (church, dinosaur)● local landmarks	Landmarks: combinations of a) static/dynamic ● b) interactive/non interactive 2D-/3D-map
Motion Control	Motion aid: non Motion technique: motion metaphor: ’walk’ ● Direction Selection: pressing a button ● Velocity: constant ● Input Condition: continuous input	Input device: mouse, joystick, keyboard

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