

VIEWPOINT OPTIMISATION FOR NAVIGATION USING DYNAMIC TETHER

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Dynamic viewpoint tethering is an innovative display technique which has been proposed to support effective navigation in large-scale virtual environments, by integrating information from different frames of reference. In this paper, we explain the modelling of a dynamic tether and report our latest research findings in investigating the optimal parametric values of tether configuration and their relations to human users' navigational performance. Tethered displays with different parametric configurations were compared. Participants were instructed to control an aircraft-shaped cursor flying in a virtual tunnel and to answer questions about the environment. The results revealed that critically damped tethers supported the best local guidance performance. No significant global awareness performance differences were observed under all display conditions.

Key Words: Dynamically tethered displays, mass-spring-damper system, virtual environments, local guidance, global awareness, navigation, virtual cameras

INTRODUCTION

In this paper we report our latest research findings in investigating dynamically tethered displays and their effects on influencing human users' navigational performance. In the earlier stage of this research, we compared a dynamically tethered display, designed according to nominal criteria, against three conventional display formats (egocentric, exocentric, and rigidly tethered viewpoints). Experimental results revealed an overall performance improvement with the dynamically tethered display in a virtual tunnel navigation task (Wang and Milgram, 2001). In this study our objective was to go further and identify an *optimal* dynamic tether configuration and its relationship to navigational task requirements.

It is widely accepted that *navigational performance* is task-dependant. This is due to the fact that navigation is a complex process which consists of both a *control* component and an *understanding* component (Wickens and Hollands, 2000). For example, driving a car involves 1) *controlling* the driving wheel and accelerator, to keep the car on the road; 2) *understanding* "where I am" in the space relative to other landmarks. These two subtasks are defined in this research as *local guidance* and *global awareness* respectively. Since requirements on these subtasks usually vary for different navigation scenarios, it is not surprising that the user's navigational performance is task-dependant. From a display design point of view, a first-person perspective (egocentric) display is usually recommended for navigational tasks in which local control (e.g., lane following or obstacle avoidance) is the primary task; while a map-display

(exocentric) is usually used for tasks in which global awareness (e.g., route planning or wayfinding) is of major concern. In situations where both components are concurrently important, a *tethered perspective* (also called a 'third-person view') has been shown to be of particular advantage relative to other conventional display formats (i.e., exclusively egocentric or exocentric). This is true also for *composite displays*, that is, arrays which consist of both egocentric and exocentric displays concurrently (Wickens and Prevelt, 1995).

In the present study, the *dynamic tether* has been proposed, 1) to provide a robust model for flexibly modifying display frame of reference to accommodate various task requirements and 2) to support superior overall navigational performance in large scale virtual environments. The current paper focuses attention upon the modelling of a dynamic tether and the effect of its dynamic characteristics on users' control performance. Our particular interest is in identifying the relationship between certain tether characteristics and the users' local guidance performance.

DYNAMIC TETHER

Conceptually, the dynamic tether is modelled as analogous to a mass-spring-damper system. The virtual camera¹ viewpoint is coupled to the avatar² through this dynamic tether (see Figure 1). The position and orientation of the avatar can be controlled by a user or by

¹ A *virtual camera* in computer graphics defines the observer's viewpoint relative to the controlled object.

² An avatar is an object which is controlled by users.

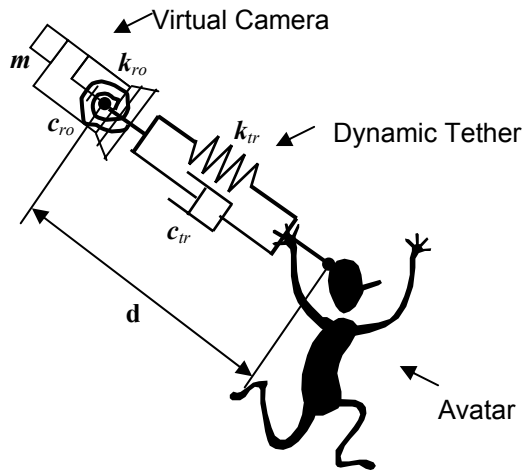


Figure 1. Dynamic tether model based on virtual coupling between avatar (human figure) and the virtual viewpoint (camera).

a third party. The movement of the avatar influences the tether's displacement, which generates a virtual force/torque on the virtual camera and an opposite force/torque on the avatar. Tether displacement also influences rotational motion, as shown in Figure 1 by the spiral at the centre of the virtual camera (suggestive of a count-clockwise mainspring). Spring force is proportional to the displacement, while spring torque is proportional to the angle of rotation and directed about a longitudinal axis of rotation.

This dynamic tether maintains the virtual camera in a stable orientation and position relative to the avatar, assuming that the two are initially aligned with a certain elevation and azimuth angle. In other words, whenever the avatar accelerates, either translationally or rotationally, the camera at the end of the tether will try to catch up with it and restabilise itself about the tether's axis. Whether or not any oscillations occur will depend on the characteristics of the dynamic tether. The virtual camera is assigned mass properties. The force and torque equations used here are:

$$\begin{aligned} \mathbf{F}_{tr} &= k_{tr} \mathbf{d}_{tr} - c_{tr} \mathbf{v}_{tr}; \\ \mathbf{F}_{ro} &= k_{ro} \mathbf{d}_{ro} - c_{ro} \mathbf{v}_{ro}; \end{aligned}$$

where

k_{tr} , c_{tr} : translational spring constant and damping coefficients respectively;

k_{ro} , c_{ro} : rotational spring constant and damping coefficient

d_{tr} , d_{ro} : avatar's relative linear and angular displacement

v_{tr} , v_{ro} : avatar's relative linear and angular velocity.

The virtual mass, spring constant and damping coefficient together define the behaviour of the tether, but only two of the three values need to be defined uniquely. In this study, the virtual mass was assigned a fixed value of one unit, and the relationship between

spring constant and damping coefficient was our primary concern.

In terms of viewpoint movement relative to the avatar, the definition of spring constant determines how fast the viewpoint can 'catch up' with the avatar. The larger the spring constant, the stronger the tether, and the shorter the time it takes for the viewpoint to reach its new equilibrium position. The extreme example is a rigid tether in which the spring constant can be regarded as infinity and there is no delay of the viewpoint movement relative to the avatar. In other words, with an infinitely rigid tether, the camera can be dragged along behind the avatar at any frequency, while the camera retains its fixed viewpoint relative to the avatar. In contrast, at the opposite extreme, if the spring constant were zero, the tether could be thought of as akin to a 'wet noodle', such that the viewpoint stays fixed no matter how the avatar moves. The tethered display would basically behave in this case like an exocentric display, in which the viewpoint does not move at all with the avatar. We argue that neither of these extreme conditions will support optimal navigational control performance, and it is our hypothesis that an optimal spring constant should lie in between these conditions.

The damping coefficient, on the other hand, affects the system's transient behaviour by changing the system damping ratio. According to vibration theory, the damping ratio is calculated from the equation

$$\zeta = \frac{c}{\sqrt{2mk}},$$

and it determines the amount of oscillation that may occur during the viewpoint movement. For example, assuming that the spring constant stays fixed, the change of damping coefficient value will affect tether behaviour in three different ways:

- 1) Whenever the damping coefficient is small ($\zeta < 1$), the tether is an *under-damped system*. Any acceleration of the avatar will cause the viewpoint to oscillate around its equilibrium position, with an amplitude determined by the magnitude of the initial exerted through the tether. The time taken for the viewpoint to stabilize would be determined by the value of the damping coefficient. The larger the damping coefficient, the shorter the time for the viewpoint to stabilise. (See Figure 2a)
- 2) Whenever the damping coefficient attains a certain critical value for which the calculation of the damping ratio yields one ($\zeta = 1$), the tether in this case is called a *critically-damped system*. Under this condition, viewpoint oscillations will not occur. (See Figure 2b)
- 3) Whenever the damping coefficient is large enough for the damping ratio to be greater than unity ($\zeta > 1$), the dynamic tether acts like an *over-damped system*. Like the critically-damped condition, no viewpoint oscillations are expected for over-damped tether displays; however, the time it takes for the viewpoint to reach its equilibrium position increases with the damping coefficient, as shown in Figure 2c.

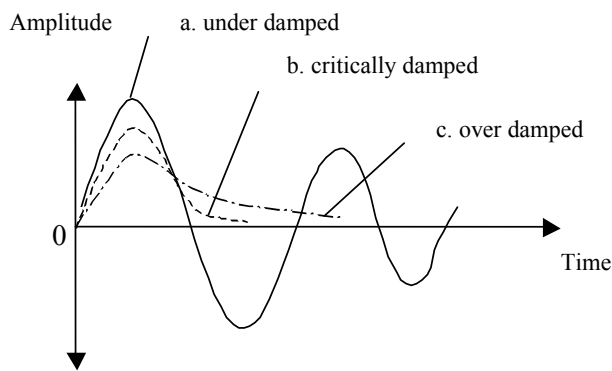


Figure 2. Dynamic transient response of dynamic tethers with different damping ratios.

The dynamic transitional viewpoint behaviours of the above three tether conditions are shown in Figure 2. For a mathematical description of these conditions, the reader is referred to any basic textbook on vibrations (e.g., Dimarogonas, 1996).

It is our hypothesis that both viewpoint oscillations (the under-damped case) and viewpoint delays (the over-damped case) will affect user's control performance detrimentally and the best control performance will be supported by a critically damped system. The objective of the experiment reported here was to test our two hypotheses regarding optimal spring stiffness and optimal damping ratio.

METHOD

Participants

The participants in this study were 7 male and 5 female students at the University of Toronto. All the participants had normal or corrected-to-normal vision, and satisfied a standard test of stereoscopic acuity. Participants were paid \$70 for their participation.

Apparatus

All participants were required to perform a set of navigational tasks in a virtual environment rendered on a SGI O2 workstation. The virtual environment was developed using OpenGL and consisted of a three dimensional virtual winding tunnel. Six different tunnel configurations were used in the test. The centre line of the tunnel was marked by a red line.

In order to alleviate the "double penalty" for tethered displays (Wickens, 2000), which is caused by the potential added ambiguity in perceiving the location of both the target and the cursor, stereoscopic viewing was implemented, to provide maximal depth cues to the participants. Imax stereo goggles were used for this purpose. Figure 3 illustrates a (monoscopic)

representation of the virtual environment and the dynamically tethered display formats used in this study. To test the hypotheses, five displays with the same spring constant and varying damping coefficients, i.e., different damping ratios, ranging from 0.5 to 4, were compared in this study.

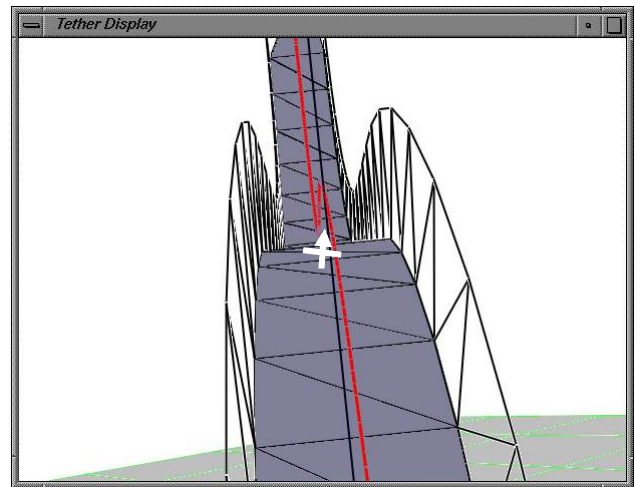


Figure 3. Snapshot from dynamically tethered display used in the study. The airplane symbol at the centre of the display indicates the avatar users being controlled.

Procedure

Participants individually completed six one-hour sessions during a three-day period. During the first session, which was used for training, participants received both written and oral instructions describing the simulation and the tasks. The experimenter remained in the room and answered general questions where necessary. In the ensuing four sessions, the participants completed four blocks of *active* flying-through-the-tunnel trials.

The actual task required the participant to control an avatar, represented by an aircraft symbol, flying along the centre of the virtual tunnel, while mentally keeping track of the shape of the tunnel simultaneously. A Spaceball was used to control the three *rotational* degrees of freedom of the aircraft (i.e. pitch, yaw and roll). (Forward motion of the aircraft was independently controlled by the software; that is, the aircraft would automatically fly forward at a constant speed.)

The order of display presentation was randomly decided. Within each block there were 15 experimental trials, each of which lasted up to one minute. The sixth session was a *passive* navigation session, in which we attempted to find out how the different display formats affected participants' subjective judgement of navigational performance. In this case, the airplane automatically flew *perfectly* through the tunnel along its centre line. Without telling the participants the airplane had been flying perfectly, we asked them to make subjective evaluations

of performance under these different display conditions, on a scale of 0 to 100. A tunnel shape recognition task was also carried out during these trials, and a brief interview was carried out at the end of this session.

In the active flying condition, RMS tracking error was used to measure performance on the local guidance subtask. A perfect score (zero error) meant that the participant had flown the aircraft perfectly along the centre of the tunnel. After completion of each navigation trial, participants were presented with a set of six physical tunnel models. One among those six tunnel models had the same shape and orientation as the virtual tunnel used in the recently completed trial and participants were required to pick it out. The accuracy of this judgement was used as an indication of the completeness of the cognitive map developed by the participants (Golledge, 1999) and thus was used as a measure of global awareness performance.

Because a within-subject design was used for this experiment, the possibility of asymmetric performance transfer existed. To understand the effect this could have had on the generalisability of the findings, an analysis of possible sequential effects was also carried out.

RESULTS

A main effect of display was found in the local guidance task ($F(4, 699) = 6.24, p < 0.001$). As shown in Figure 4, local guidance performance was best observed under the critically damped tether condition. A Tukey analysis showed significant performance differences among the under-damped condition ($\zeta = 0.25$), the critically damped condition ($\zeta = 1$), and the over-damped tether condition ($\zeta = 2$).

RMS control error
(in units of distance)

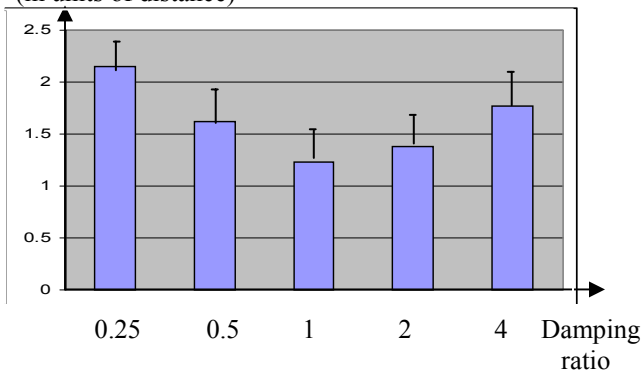


Figure 4. Effect of damping ratio on local guidance performance.

The tunnel shape recognition scores (global awareness measure) didn't reveal any significant differences across display conditions ($F(4,699) = 1.40, p = 0.182$). Significant differences were revealed in the subjective

passive-flying evaluation ($F(4, 699) = 9.73, p < 0.001$), however, with the post hoc analysis showing that the under-damped tether condition ($\zeta = 0.25$) scored significantly lower than all the other display conditions.

DISCUSSION AND CONCLUSION

Dynamic tether and local guidance performance

Through observation and analysis, two well known factors have been identified to affect users' local guidance performance: control/display alignment and control/display congruence. Display formats which violate these factors will cause deterioration in control performance. Most of the experimental findings in this study can be explained by this. For example, the viewpoint oscillations caused by the under damped tethered display failed to maintain good control/display alignment, thus, leading to the poor RMS score. The experimental findings also showed that the critically damped tether supported the best local guidance performance. This reflects the fact that the users have tolerance to changes in viewpoint and are able to adapt to it. This finding provides the display designer with a buffer in design space. As long as the tether configuration lies around the critically-damped region, stable control performance should be maintained.

Tunnel shape recognition as a secondary task

The tunnel shape recognition performance was used in the study as a measure of participants' global awareness performance. In hindsight, it is not surprising that no significant performance differences were observed since the same tether length and nominal viewpoint positions were used in the testing. These two factors together determine the amount of context information the user can perceive, as well as the amount of 'preview' information the user can get. It is our intention in our next experiment to investigate how these characteristics affect global navigation.

Successful navigation in virtual environments is critical in tasks such as telemanipulation, endoscopic surgery, virtual training systems, certain CAD systems and computer games. Therefore, it is important to design visual displays which respond appropriately to the operator's control inputs without imposing excessive mental workload. The results of this study should provide useful guidelines for the design of such displays. The use of dynamic tethering may reduce local control errors in navigation, as well as the operator's need to perform difficult mental transformations, by maintaining appropriate alignment between display and control reference frames.

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