DYNAMIC TETHERING FOR ENHANCED REMOTE CONTROL AND NAVIGATION

Herman W. Colquhoun Jr. & Paul Milgram
Department of Mechanical and Industrial Engineering
University of Toronto, Canada
{herman; milgram}@etclab.mie.utoronto.ca
http://etclab.mie.utoronto.ca/

Misalignments between display and control reference frames complicate execution of many remote control tasks by loading the operator's attentional resources with mental transformations. It is thus important to maintain alignment between an operator's controls and her view of the controlled object or task space. Maximising the operator's situational awareness within this task space by providing an optimal frame of reference also simplifies task execution. Traditional rigid tethering integrates desirable egocentric and exocentric aspects of a display by connecting an exocentric view of the task space to the system being controlled. This paper introduces the concept of *dynamic tethering* (a superset of rigid tethering) which also preserves the principle of the moving part while maintaining control-display motion compatibility. Two experiments are presented, which show that compliance with these principles decreases the frequency of control reversals, improves reaction times, and decreases the RMS error associated with tracking performance.

INTRODUCTION

The frame of reference chosen for a telemanipulation task has an influence on human performance in many applications, such as: space operations (Wettergreen et al, 1999), aviation (Johnson and Roscoe, 1972), remote vehicle control (McGovern, 1991; Craig et al., 1983; Milgram and Colquhoun 1999a), scientific visualisation (McCormick et al., 1998), endoscopic surgery (Holden et al., 1999; Milgram and Colquhoun, 1999b), land navigation (Glumm et al., 1998; Kitamura et al., 1998), and telerobotics (Sheridan, 1992). Adequate navigation and control of remote devices are critical to successful task completion and can weigh heavily on the attentional resources of the operator. It is therefore important to design displays to provide appropriate feedback about such devices and their environment and support these tasks without adding too much complexity. It is also important to maintain appropriate alignment between an operator's controls and her view of the controlled object, because misalignments between display and control reference frames complicate task execution by loading the operator's attentional resources with mental transformations. Another objective of display design is to maximise the operator's global situational awareness within the task space. It is widely recognised that global awareness increases with the exocentricity of the frame of reference while the awareness needed for local guidance decreases accordingly, as illustrated in Figure 1.

The concept of *viewpoint tethering* facilitates the integration of necessary information from egocentric and exocentric displays by linking an exocentric view of the task space to the telemanipulator. Wickens (Wickens et al, 1994; Wickens & Hollands, 2000) describes such a link as a "3D [rigid] tether" (illustrated in Figure 1). This virtual camera-manipulator connection allows both global awareness and local guidance information to be maintained simultaneously. Egomotion (i.e., the movement of one's viewpoint with corresponding control inputs) within the resulting display ensures that a consistent control-display relationship is preserved. Also, because the attached viewpoint is exocentric, global situational awareness is promoted. On the other hand, local navigational awareness is also maintained when the viewpoint is only slightly displaced from its "nominal" position (e.g., the cab of the excavator shown in Figure 1). However, applying a *rigid* tether results in a display that violates the principle of motion compatibility, since the operator will observe world motion which is opposite to the direction of her input. In addition, because the output of such a display closely resembles that of a compensatory tracking system, certain well-known disadvantages associated with motion cue depletion may result.

It is proposed that relaxing the constraints associated with the "rigid" tether may help to alleviate some of these problems. In particular, modelling the tether as a mass-spring-damper system allows its rigidity properties to be modified. This *dynamic tether* creates a display that combines elements of both compensatory and pursuit tracking systems. Early work by Senders and Cruzen (1952) indicated that "a good deal might be gained by using a display that has the target … move slightly yet keeps the scaling advantages of compensatory presentations". The dynamic tether is also an example of frequency separation. Fogel introduced the "frequency-separation" concept with his Kinalog display in 1959, and Roscoe conducted further research in the 1970's. The above-mentioned theoretical characteristics of the dynamic tether imply that tracking performance should be improved when this construct is applied.

The objective of this paper is to present the results of an initial investigation into the principle of dynamic tethering, which show how docking and tracking performance measures (i.e., reaction time, frequency of control reversals, and RMS error in the frequency domain) differ between non-tethered, rigidly-tethered, and dynamically-tethered displays. Full details of the experiment may be found in Colquhoun (2000).

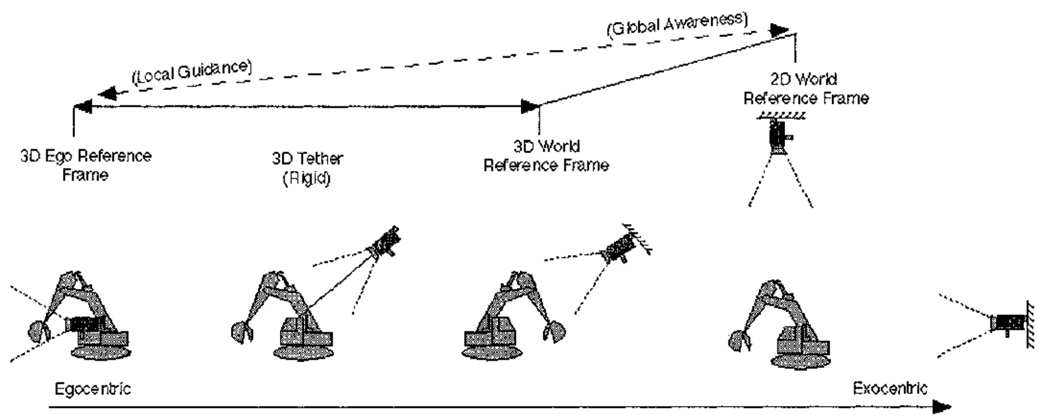

Figure 1 Centricity continuum: The transition from ego- to exocentric viewpoints (adapted from Wickens et al, 1994)

METHOD

Participants

Ten paid subjects (2 women, 8 men) of varying backgrounds participated in this experiment. All subjects had normal or corrected-to-normal vision, and ranged in age from their late teens to late thirties. Three of the participants were left-hand dominant, but all indicated that they used their right hands when manipulating computer input devices, such as a joystick or a mouse. Two of the left-handed subjects performed counterbalanced trial orders.

Experimental Setup

A Silicon Graphics Impact graphics system was used to present docking and tracking tasks on a high-resolution 17-inch monitor. The display refresh rate was 60 Hz; however, because screen update rate fluctuated with computational load on the system, the actual resulting *update* rate varied between 25 and 35 Hz. The interface was designed such that it provided feedback and instructions to the user, and logged experimental data with little intervention by the experimenter.

Subject eye-to-screen distance from the monitor was approximately 50 cm. The height of the subject's eye level relative to the monitor was not controlled, since it was more important that the subjects' seat heights be adjusted such that their arms rested comfortably on the armrest of the controller. This helped to ensure that fatigue would not set in due to inappropriate positioning of the subjects' arms while tracking the on-screen targets.

Experimental Design

Two experiments were performed, both as factorial designs, comprising a rotating cursor which was to be aligned with a rotated target. The first was a *6x14x2x5 factorial, within-subjects design docking experiment.* There were:

- six levels of displacement, or angular departure (AD), between the presented cursor and target markers,
- fourteen levels of cursor orientation (CO), with respect to a nominal zero position, or base vector,
- two levels of viewpoint perspective (VP),
- five levels of dynamic tethering (DT), in terms of natural frequencies: {w00: 0 Hz, w01: 2.65×10^{-3} Hz, w02: 2.29×10^{-2} Hz, w03: 1.985×10^{-1} Hz, and w99: ∞ Hz}.

It is important to understand the distinctions between the three different independent variables presented above as angular displacements. The first, AD, represents the size of the step input to the docking task. The second, CO, represents the angular rotation of the cursor relative to the defined forward facing base vector, and is unrelated to AD, the magnitude of the docking task input. The third, VP, represents the angular rotation of the camera viewpoint about its pitch axis relative to the 3D-cursor control system.

The second design was a *10x2x5 factorial, within-subjects design tracking experiment.* In particular, there were:

- ten levels of tracking inputs, reflecting the average cursor angular displacement (CAD) from a nominal zero position,
- two levels of viewpoint perspective (VP, same as above),
- five levels of dynamic tethering (DT, same as above).

It is again important to understand the distinctions between the different angular independent variables presented above. CAD is analogous to CO for the docking task, but represents a mean level rather than a single value. There is no variable analogous to AD above, since this variable is incorporated into the amplitude of the forcing function disturbance.

RESULTS AND DISCUSSION

Reaction Time. Figure 2, for the docking experiment, indicates that tethering in general decreases the time it takes to decide which *direction* of input is required to align the cursor with the given target orientation. Although the reaction times measured when using tethers w01, w02, w03, and w99 are not significantly different from each other ($p > 0.05$), the mean reaction times for the single *non-tethered* case, w00, is significantly greater than all of the other four ($F(4,36)=18.343$, $p<0.0001$). Figure 3 illustrates this same result, where we easily see the separation of the non-tethered w00 data from the rest. No significant interaction between cursor orientation and the first five tether types listed in Figure 3 ($p>0.05$), but this may be due to the fact that variations in the measures of reaction time obscure any potential interaction. The corrected w00 data show a slight tendency toward increased reaction time as the cursor alignment with the physical controls decreases, i.e. as CO increases, when all occurrences of control reversal are removed from the data for the non-tethered case (i.e., w/o CRs). Control reversals are initial rapid control movements in the wrong direction, and as predicted by the principle of speed-accuracy trade-offs, the existence of such reversal errors should bias the reaction time measures downward. Removal of control reversal data thus presents a more true picture of how mental operations affect reaction times as a function of varying degrees of control-display misalignment (CO).

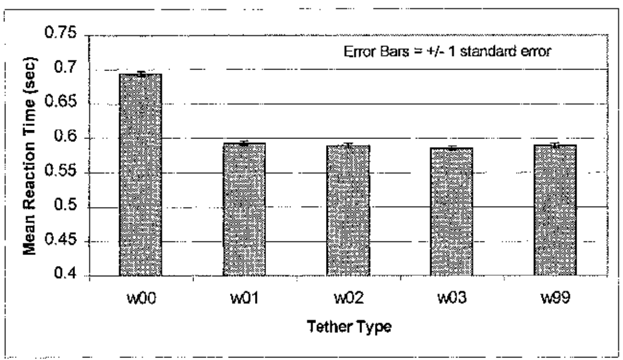

Figure 2 Effects of dynamic tethering (DT) on reaction time

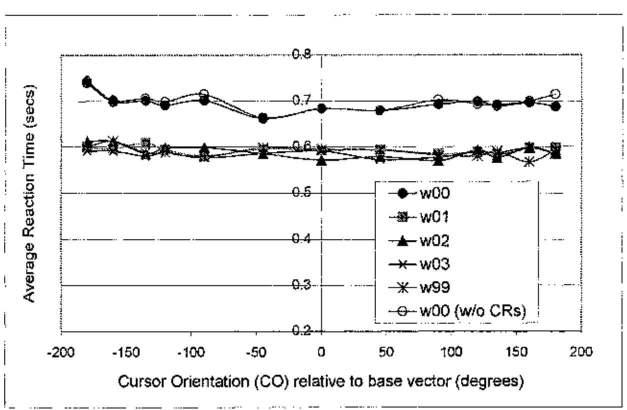

Figure 3 Reaction times: CO x DT interaction

Control Reversals. Figure 4, also from the docking experiment, illustrates in a different way how tethering can reduce the frequency of operator error in the form of control reversals. On average there is no significant difference between the results obtained from the four tethered cases (w01, w02, w03, and w99); however, there is a significant increase in the occurrence of control reversals in the non-tethered case, w00, $F(4,36)=12.889$, $p< 0.0001$. Figure 4 illustrates why this is so. As the misalignment between the hand-controls and the displayed cursor orientation (CO) increases:

(a) from 0° to +/- 45°, the proportion of control reversals that occur are due to chance error and thus the data for the five tethers cannot be distinguished,
(b) approaching +/-90°, the non-tethered display permits increased controller-cursor incongruence and we can see that the probability of control reversals occurring rapidly increases,
(c) between 90° and 180° (and -90° to -180°), the number of occurrences levels off and then increases drastically again at +/- 180°.

These increases in operator error are due to the cognitive loading incurred because of the mental rotations involved in mapping the displaced cursor to the forward facing controller.

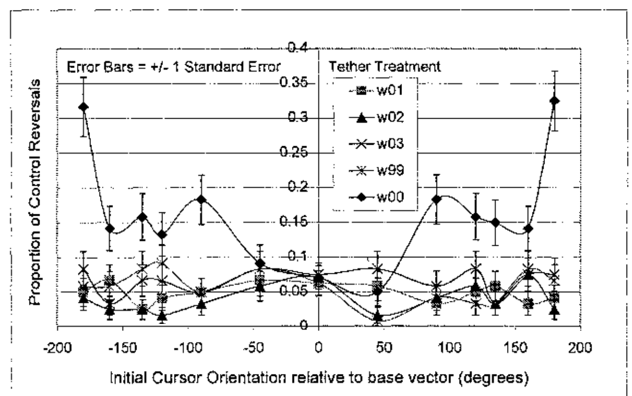

Figure 4 Control reversals: DT x CO interaction

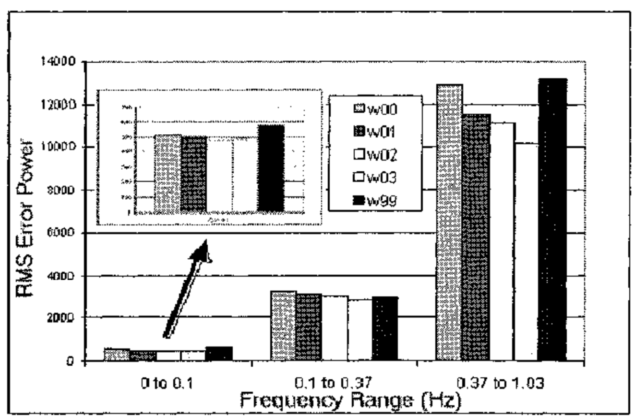

Figure 5 Plot of Spectral Power over three frequency ranges

Spectral Analysis. A spectral analysis of the tracking data (from the tracking experiment) was performed in order to investigate the effects of dynamic tethering performance in the frequency domain. Figure 5 illustrates the spectral error power contained over three critical frequency ranges contained within the forcing function. The graph shows that performance at all frequencies was best (i.e. rms error lowest) when tethers w02 and w03 were used. The graph also indicates that at higher tracking frequencies, which dictate tracking performance (see Poulton, 1974), one's ability to perceive both absolute and relative motion of the cursor and target becomes increasingly important (i.e., the difference in performance with each tether is more pronounced).

Subjective Evaluations. Based on their exposure to both experiments, subject assessment that there was a slightly more degrading effect of tether rigidity (w03 and w99) on their performance relative to the other, less rigid tether modes (w00, w01, w02) was marginally significant ($F(4,36)=2.235$, $p=0.085$). These results are presented in Figure 6. The most significant finding, shown in Figure 7, was that obtained from the measurement of subjects' reaction to on-screen motion caused by their control input. Subjects' responses to the resulting on-screen motion was one of disorientation for the highly rigid tethers (w03 and w99) to a much greater degree ($p<0.001$) than was perceived with the less rigid tethers (w00, w01 and w02).

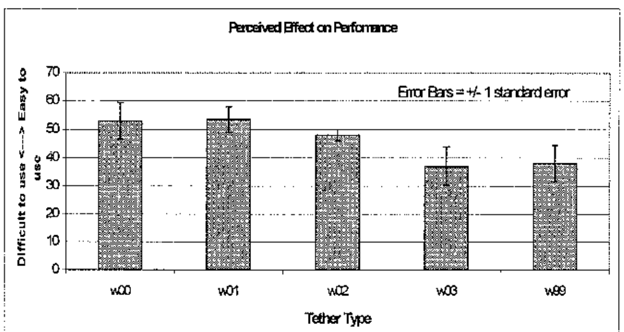

Figure 6 Perceived effect of rigidity on performance

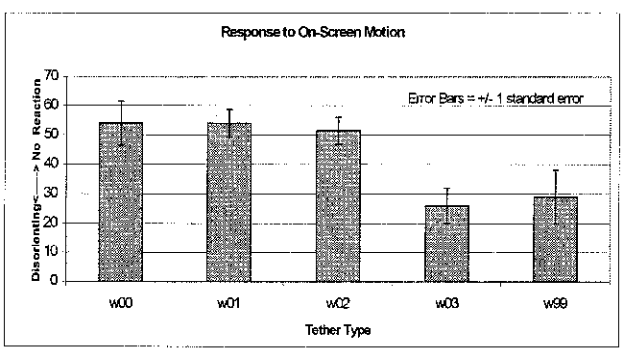

Figure 7 Subjective rating of response to on-screen motion

In reviewing the objective docking and tracking measures and subjective performance measures recorded in this study, one tethering mode, w02 ($\omega_n=0.023$ Hz, $\zeta=1.0$), appears to rank better than the rest. This mode elicited the best performance for the given tasks in terms of control errors and reaction times, RMS tracking scores, and less subjective ratings of disorientation. This result was not unexpected, as it was our belief that a "moderate" set of tether parameter values should lead to an optimal trade-off among the various advantages and disadvantages associated with each extreme of the tether continuum. Further research must be performed, however, to investigate, in more detail, the manner in which optimal tether break frequency relates to the frequency composition of the input tracking function.

ACKNOWLEDGEMENTS

The authors acknowledge Precarn Associates and MacDonald Dettwiler Space and Advance Robotics Ltd. (formerly Spar Aerospace Ltd.) for their support of this research.

REFERENCES

Colquhoun, H.W. Jr. (2000) Dynamic Tethering for Enhanced Remote Control and Navigation. Unpublished M.A.Sc. dissertation, University of Toronto.

Craig, K. M., Hartzell, J.E., and Dunbar, S.L. (1983), "Helicopter pilot response as a function of compatibility of the control-display configuration". *19th Annual Conference on Manual Control*, p.100.

Fogel, Larry J., (1959). "A New Concept: The Kinalog System", *Journal of the Human Factors Society*, Vol. 1, No. 2, pages 30-37, April 1959.

Glumm, M.M., Marshak, W.P., Branscome, T.A., Wesler, M.Mc., Patton, D.J., Mullins, L.L., (1998). "A Comparison of Soldier Performance Using Current Land Navigation Equipment With Information Integrated on a Helmet-Mounted Display". Army Research Laboratory, April 1998. (ARL-TR-1604)

Holden, J.G., Flach, J.M., and Donchin, Y., (1999). "Perceptual-motor coordination in an endoscopic surgery simulation". *Surgical Endoscopy: Ultrasound and Interventional Techniques*, 1999, vol. 13.

Johnson, S.L., and Roscoe, S.N. (1972). "What Moves, the airplane or the world?" *Human Factors*, 14, 107-129.

Kitamura, Y., Fukatsu, S., Masaki, T., and Kishino, F., (1998). "Intuitive Control of 'Bird's Eye' Overview Images for Navigation in an Enormous Virtual Environment". ©The Eurographics Association, 1998. Blackwell Publishers.

McCormick, E. P., Wickens, C. D., Banks, R., and Yeh, M., (1998). "Frame of reference effects on scientific visualization subtasks," Human Factors, vol. 40, no. 3, pp. 443-451.

Milgram, P., and Colquhoun Jr., H.W. (1999a). "A Taxonomy of Real and Virtual World Display Integration". Chapter 1 in Y. Ohta and H. Tamura (Eds.), Mixed Reality: Merging Real and Virtual Worlds, Ohmasha, Ltd., © 1999, pp. 5-30.

Milgram, P., and Colquhoun, H. W., (1999b). "A Framework for Relating Head-Mounted Displays to Mixed Reality Displays", *Proceedings of the Human Factors and Ergonomics Society, 43rd Annual Meeting*. Houston, Texas, September 27 to October 1, 1999, pp. 1177-1181.

McGovern, D., in Ellis, R. Stephen (Ed), (1991). Pictorial communication in virtual and real environments © 1991, Taylor & Francis Ltd., New York.

Poulton, E. C., (1974). Tracking Skill and Manual Control. Academic Press, New York, © 1974.

Senders, J.W. and Cruzen M (1952). "Tracking performance on combined compensatory and pursuit tasks" (WADC Tech. Rep. 52-39). Wright-Patterson Air Force Base, Ohio: Wright Air Development Center.

Sheridan, T. B. (1992). "Human Factors Considerations for Remote Manipulation, Advanced Guidance and Control Aspects in Robotics", AGARD Lecture Series 193, Ontario, Canada.

Wettergreen, D., Bapna, D., Maimone, M., and Thomas, G. (1999). "Developing Nomad for robotic exploration of the Atacama Desert," *Robotics and Autonomous Systems*, 26: 127-148.

Wickens, C.D. & Hollands, J.G. (2000) Engineering Psychology and Human Performance, Third Edition. Prentice-Hall.

Wickens, C.D., Liang, C., Prevett, T., and Olmos, O., (1994). "Egocentric and Exocentric Displays for Terminal Area Navigation". Technical Report, January 1994. Aviation Research Laboratory Institute of Aviation, University of Illinois at Urbana-Champaign.