INVESTIGATION OF FEEL FOR 6DOF INPUTS: ISOMETRIC AND ELASTIC RATE CONTROL FOR MANIPULATION IN 3D ENVIRONMENTS

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An increasing need exists for both a theoretical basis and practical human factors guidelines for designing and selecting high degree-of-freedom (DOF) computer input devices for 3D interactive environments such as telerobotic and virtual reality systems. This study evaluates *elastic* versus *isometric* rate control devices, in a 3D object positioning task. An experiment was conducted with a stereoscopic virtual reality system. The results showed that the elastic rate controller facilitated faster task completion time in the first of four phases of the experiment. The results are discussed in light of psychomotor literature. While the richer proprioceptive feedback afforded by an elastic controller is necessary for achieving superior performance in the early stages of learning, subjects performed equally well with the *isometric* controller in later learning stages. The study provides evidence to support a theory of skill shift from closed-loop to open-loop behaviour as learning progresses.

INTRODUCTION

Virtual reality, telerobotics, and 3D scientific data visualisation have all been receiving increasing attention from industry, academia and the public in general. In relation to human factors, these technologies are capable of providing advanced tools for building powerful human-machine interfaces; however, much human factors research is still needed to guide the development of these tools (e.g. Ellis, Kaiser, & Grunwald, 1991; Sheridan, 1992). Research currently underway at the University of Toronto aims at systematically addressing one particularly important aspect of interactive 3D systems – 6 DOF (degree-of-freedom) input controls.

The design of controls is central to human factors study. Early work in this area appears in many handbooks (e.g. Chapanis, 1972). Research on control and input devices can also be found in specialised disciplines, such as aviation (Orlansky, 1949), teleoperation (Brooks & Bejczy, 1985) and human computer interaction (Buxton, 1990). In reviewing early works related to control feel, Burrows (1965) pointed that far less theoretical knowledge than expected exists on the topic, due to the complex multi-factorial nature of the problem. Although Burrows did overlook some important early works (e.g. Gibbs, 1954; Bahrick, Fitts & Schneider, 1955; Howland & Noble, 1953), our understanding of control feel is still far from complete.

Zhai and Milgram (1993) proposed a taxonomy for conceptually classifying the diversity of possible designs in 6DOF input. Two of the three dimensions of their taxonomy, namely sensing mode and transfer function, are shown in Figure 1. The four options in Figure 1, i.e, isotonic position, isotonic rate, isometric position and isometric rate control schemes were evaluated in that study (Zhai & Milgram, 1993). A strong interaction was found between the control order (position versus rate control) and the sensing mode (isotonic versus isometric). Isotonic position as well as isometric rate yielded much better performance than the other two schemes (isotonic rate and isometric position). Because of the similarity with motor movements in daily life, isotonic position control is more intuitive and produced better *initial* performance scores than the isometric rate control, but on the average this advantage vanished after 20 minutes of practice. The disadvantages of the isotonic position mode are its large operating volume and much more fatiguing characteristics due to unsupported hand movements (Zhai, 1993).

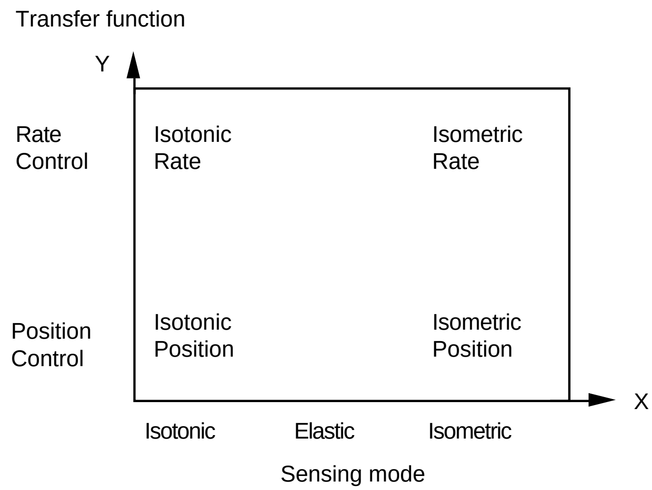

Figure 1. Two dimensions of input design

Of the many possible reasons for the superiority of the isotonic position and the isometric rate control over the others, *compatibility* and *control feel* are of particular importance. Compatibility means that some properties of a particular sensing mode (e.g. isometric) match with certain modes of transfer function (e.g. rate control). For example, the self-centering nature of isometric sensing tends to facilitate rate control, which requires a pair of reversed actions for stable control.

The feel of a controller is closely related to proprioceptive feedback. Neurophysiological research has found that four distinctive types of somatosensory receptors, namely *joint receptors*, *Golgi tendon organs*, *muscle spindles* and *cutaneous receptors*, can be involved in providing information to the central nervous system (CNS) (see Sage, 1977; Schmidt, 1988 for a review). Each type of the receptor has its unique functions and the CNS integrates signals from these different information sources.

Since joint angles in the user's limb are stationary when operating an isometric controller, only three types of somatosensory receptors can be involved in providing proprioceptive information. In contrast, an elastic (spring-loaded) controller will involve all four types of proprioceptive information and, since it has a self-centering effect, it also conforms with the compatibility principle proposed above.

The experiment reported upon in this paper has been conducted to compare a 6DOF elastic rate controller and a 6DOF isometric rate controller on a 3D object positioning task. With all other factors kept similar, the elastic controller is hypothesised to produce better performance.

EXPERIMENT

Experimental Apparatus

The experiment was conducted using the MITS (Manipulation in Three Space) system developed by the author. MITS is a non-immersive stereoscopic virtual reality environment, based on a SGI IRIS 4D/310 GTX graphics workstation equipped with a Spaceball™, an Ascension Bird™, CrystalEyes™ stereoscopic glasses and some self-designed controllers. MITS allows the user to perform dynamic 6 DOF manipulation tasks, such as target acquisition, critical tracking (Jex, McDonell & Phatak, 1966), and compensatory and pursuit tracking (Poulton, 1974) with a variety of 3D objects in various display and control modes. The MITS system automatically records detailed and summary data of user control behaviour and performance score and presents knowledge of results (KR) feedback whenever necessary.

In this experiment, the *isometric rate* control mode is implemented by means of a Spaceball™ (Model 2003). The *elastic rate* control mode is implemented with a 6DOF device designed by the author.

Much attention was invested in ensuring that a fair comparison was made between the two experimental conditions. The two controllers used in the experiment were of similar size and each was mounted on table at a fixed distance (40 cm) from the computer screen.

The control gains (sensitivity) for each manipulation scheme were optimised through systematic parameter searching with one experienced user as subject. U shaped performance curves were found with variations in gain, for both control modes (Figures 2 and 3). The elasticity of the elastic rate controller was optimised in a similar fashion.

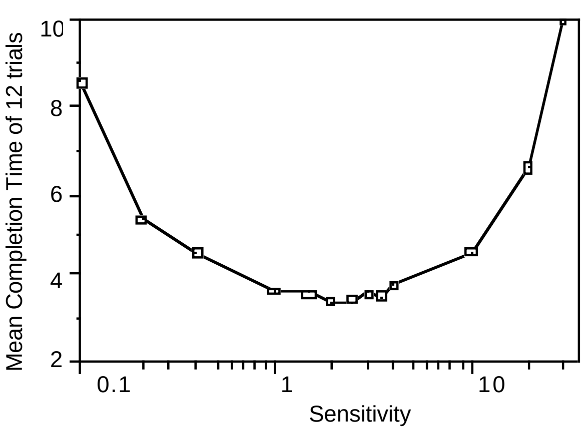

Figure 2. Optimal gain search of the isometric rate control

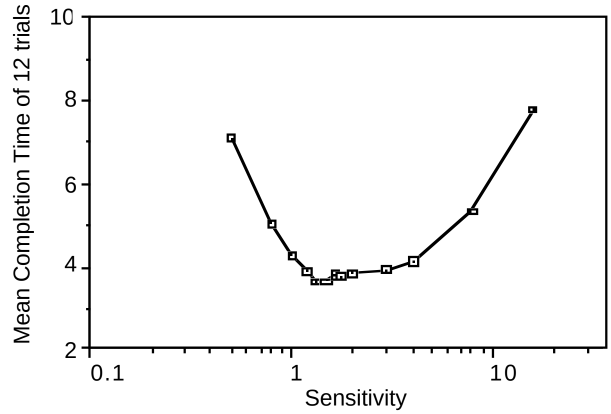

Figure 3. Optimal gain search of the elastic rate control

Experimental Task

A three dimensional object positioning task was used in this experiment. Subjects were asked to move the tetrahedron appearing off centre (the cursor) as quickly as possible to align it with the fixed tetrahedron in the centre of the screen (the target) (Figure 4). Whenever a corner of the cursor reached the corresponding star of the target, the star changed its colour, as an indication of capture. Whenever all four corresponding corners stayed matched for at least 0.8 seconds, the trial was completed.

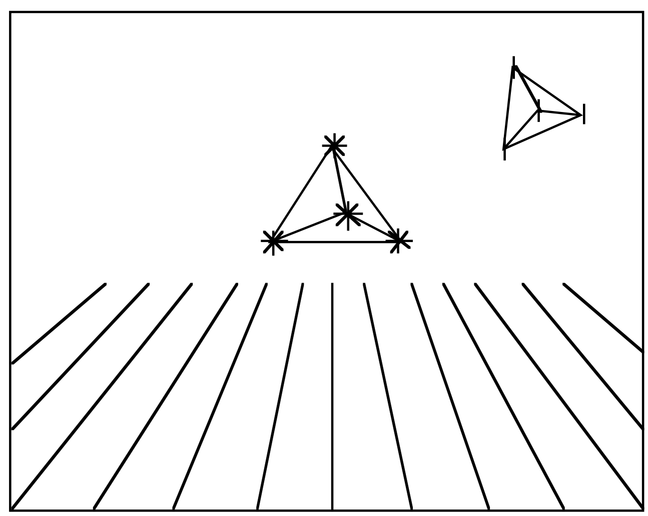

Figure 4. Experimental task

The Display

Since the purpose of the research programme is explicitly to evaluate 6DOF manipulation schemes, our emphasis in designing the display for this experiment was to provide the largest possible number of 3D spatial cues, so that any bottlenecks in performance of the task would result from the particular manipulation scheme and not from the display. The display comprised a 120 Hz sequential switching stereoscopic display system, which has been shown to be a necessary feature for this kind of experiment, because without stereopsis, much greater orientation
ambiguities would be perceived by the subjects. To enhance the 3D effect, wide angle perspective projections

and inter-position cues were also adopted. The tetrahedrons were drawn in wire-frame so that all edges and corners of the objects could be perceived simultaneously. Subjects were asked to sit on a chair 60 cm away from the computer screen.

Subjects

To avoid the effects of asymmetrical skill transfer (Poulton, 1966; 1974), a strictly between subjects design was employed in this experiment. Each of the subjects served in only one condition: isometric rate or elastic rate control. One of the pitfalls of between-subjects designs is that individual differences may bias experimental results. Pitrella & Krüger (1983) have suggested using matching tests to form equal groups for tracking experiments. However, choosing a suitable matching test is a very delicate task, since the test has to be sufficiently similar to the experimental conditions so that measured and matched subjects' capabilities are relevant to the experimental task. One the other hand, the test has to be such that the amount of skill transferred from the matching test to each of the experimental conditions is equal. It is often impossible to design a test to fit all these requirements.

In this experiment, randomisation and a sufficiently large number of subjects were used to dilute the possible individual differences effect. 35 paid volunteer subjects were recruited by advertising through posters and electronic network news groups on the University of Toronto campus. All subjects were screened using a Bausch & Lomb Orthorater. Five of the subjects were rejected for having poor (corrected) near vision acuity, another four were rejected for having weak stereo-acuity.

Among the 26 subjects accepted, two were left-handed, as determined by the Edinburgh inventory (Oldfield, 1971). One of them was assigned to the elastic rate control and the other was assigned to the isometric rate control condition. The controls were set at the subjects' dominant hand side. Three of the 26 accepted subjects were female. Two were put into the elastic rate control mode and one was assigned to the isometric rate mode.

The rest of the 21 male right handed subjects were randomly assigned to the two conditions.The balance of composition of the two groups of subjects was checked by age, profession etc. No obvious bias against any condition could be found.

The accepted subjects' ages ranged from 16 to 38, with the majority in their early and mid-20's. Most of the subjects were engineering or computer science under-graduate students. All had experience with computer mice but none of them had used a 6DOF input device before the experiment.

Experimental Procedure

Each experiment session consisted of a 10 minute vision screening test, 5 minutes of instruction, 40 minutes of experimenting, and a 5 minute questionnaire survey. The 40 minute experiment was divided into four phases. Each phase comprised 10 minutes of training, followed by 12 trials of data collection. Each training phase consisted of demonstrations and coaching by the experimenter, combined with practice trials. The data from the 12 trials were composed of 3 blocks of 4 trials, each block comprising 4 different randomly shuffled starting locations for the manipulated tetrahedron (the cursor).

EXPERIMENTAL RESULTS

Performance

Figure 5 presents the primary results of this experiment. Due to the fact that task completion times were not normally distributed, but skewed towards the short scores, a non-linear (logarithmic) transformation of the task completion times was taken as the dependent variable in the data analysis.

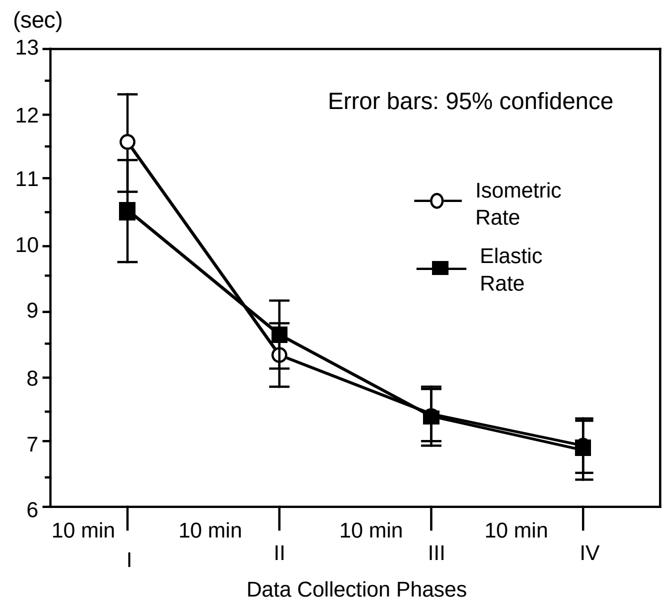

Figure 5. Task mean completion time in four phases of experiment

Taking data from all four phases of the experiment, analysis of variance showed that learning phase is the most significant performance effector ($F(3, 1237) = 95.7$, $p<.0001$), indicating that subjects acquired much more skill towards the end of a session (as illustrated in Figure 5). Another significant factor ($F(3, 1237) = 4.41$, $p = 0.004$) was initial target location, resembling the Index of Difficulty in a one dimensional Fitts' law task. Two of the initial locations required significantly longer travel to the target position (and orientation). No significant differences were found between the average time scores over the four phases of the two input control schemes ($F(1, 1237) = 2.65$, $p = 0.10$).

More detailed data analysis was conducted within each phase of the experiment. In the first phase (after 10 minutes of learning), the *elastic rate* control (mean value 10.5 s) afforded significantly better performance ($F(1, 307) = 6.69$, $p = 0.01$) than the *isometric rate* control (mean value 11.6 s). The difference between the two control modes becomes insignificant in phase II ($F(1, 307) = 0.36$, $p = 0.55$), phase III ($F(1, 307) = 0.30$, $p = 0.59$) and phase IV ($F(1, 307) = 0.20$, $p = 0.66$).

Subjective Ratings

Immediately after each session of the experiment, the subjects were asked to comment on the ease of use/ difficulty and the degree of fatigue of the controller that s/he had used. Because of sensitivity vulnerablity, adjectival biases and non-linearity, the subjective data were not subjected to statistical analysis. The major motivation for conducting the questionnaire survey was to acquire valuable feedback from the subjects. The data do not suggest large differences of subjective opinions between the two controllers (Figure 6 and Figure 7).

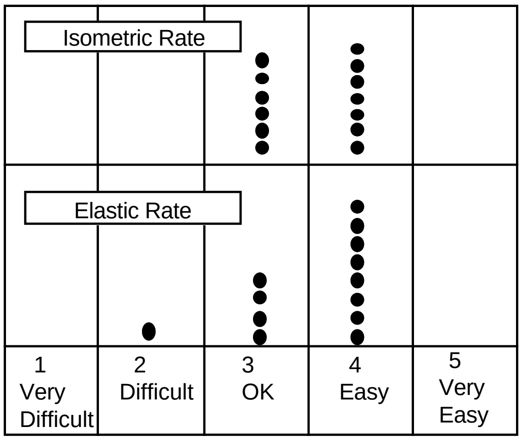

Figure 6. Subjective ratings of ease of use

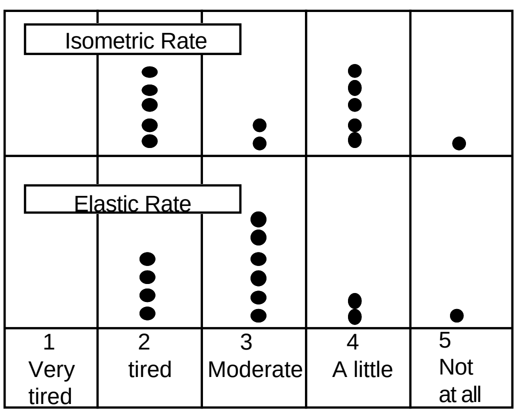

Figure 7. Subjective ratings of fatigue

DISCUSSION

A simple explanation of the performance score is that the elastic rate control *is* better than the isometric rate control scheme in general. Due to the nature of the positioning task, which is relatively easier than a continuous tracking task, the advantage of the elastic rate mode was shown only in the first phase of the experiment. In the later phases, performance ceiling (floor) effects concealed the differences between the two modes.

A deeper level of analysis presented here is related to motor learning theories. The centralist view, which emphasises the dominance of centrally stored motor programs, versus the peripheralist theory, which stresses the importance of information feedback, have been the subject of a longstanding debate in psychomotor studies. (See Schmidt, 1988; Singer, 1980; Stelmach, 1979 for a general overview. See Gibbs, 1954; Nortterman & Tufano, 1980 in relation to controls). More recent theories com--promise extreme views, exemplified by Schmidts' schema theory (Schmidt, 1988), which contends that both open loop and closed loop behaviours exist, and that the relative roles of central resources and feedback information depend on the pace of the task and the experience that the subject has with a particular type of task. Much evidence has shown that, as learning progresses, human motor strategies shift from closed loop behaviour towards open loop behaviour, typically with respect to the decreasing importance of the visual feedback. It has been recognised that three modes of tracking behaviour can be identified: error nulling, input reconstruction and precognitive behaviour (Krendel & McRuer, 1968; Jagacinski & Hah, 1988). In the error nulling mode, subjects primarily rely on visual, exteroceptive information to minimise the tracking error. In input reconstruction mode, subjects additionally utilise proprioceptive information to form control actions. In precognitive mode, subjects depend on open-loop tracking patterns reproduced from memory and the roles of exteroceptive and proprioceptive feedback are less important. With practice, subjects' behaviour progresses from the error nulling mode to the input reconstruction mode to the precognitive mode. The source of information shifts from the visual exteroceptive to the proprioceptive and then to internal memory in this process.

Supplementing the above theories, the results of this experiment imply that fewer sources of proprioceptive information are needed as practice continues and some internal open loop mechanism presumably substitutes the missing proprioceptive feedback. Therefore similar performance between the elastic and the isometric rate controls was found in the late stage of learning.

CONCLUSIONS

Augmenting all four types of proprioceptive feedback, a 6DOF elastic controller showed some superiority over an isometric rate control which involves only three types of proprioceptive feedback. This advantage is evident only in the early stages of learning and vanished after 20 minutes of practice.

Practically, this experiment provides some empirical data and a basis for 3D interactive interface design in telerobotic systems, data visualisation or virtual reality. Although elastic sensing is generally recommended for 6DOF rate control, isometric sensing can yield similar performance, if some practice is allowed and if target acquisition is a primary component in the 3D interactive system application. For tasks such as navigation in 3D space which involve more tracking behaviour, the relative performance of the two control modes has yet to be investigated.

Theoretically, as a supplement to much empirical evidence that suggests a shift from visual to proprioceptive feedback as practice continues, the present research provides evidence of a psychomotor behaviour shifting from closed-loop skill towards open-loop skill with various levels of proprioceptive feedback.

FUTURE RESEARCH

We are currently investigating 6DOF *pursuit* tracking with the two control techniques used in the present experiment. In addition, we are exploring other design options within the design space taxonomy proposed in (Zhai, Milgram & Drascic, 1993; Zhai & Milgram, 1993).

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