Quantifying Coordination in Multiple DOF Movement and Its Application to Evaluating 6 DOF Input Devices

Shumin Zhai
IBM Almaden Research Center
650 Harry Road, San Jose, CA 95123, USA
+1 408 927 1112 zhai@almaden.ibm.com

Paul Milgram
Dept Mech. & Ind. Eng., University of Toronto
Toronto, Ontario, Canada, M5S 3G8
+1 416 978 3662 milgram@mie.utoronto.ca

ABSTRACT

Study of computer input devices has primarily focused on trial completion time and target acquisition errors. To deepen our understanding of input devices, particularly those with high degrees of freedom (DOF), this paper explores device influence on the user's ability to coordinate controlled movements in a 3D interface. After reviewing various existing methods, a new measure of quantifying coordination in multiple degrees of freedom, based on movement efficiency, is proposed and applied to the evaluation of two 6 DOF devices: a free-moving position-control device and a desk-top rate-controlled hand controller. Results showed that while the users of the free moving device had shorter completion time than the users of an elastic rate controller, their movement trajectories were less coordinated. These new findings should better inform system designers on development and selection of input devices. Issues such as mental rotation and isomorphism vs. tools operation as means of computer input are also discussed.

Keywords

Input devices, interaction techniques, evaluation methods, 6 DOF control, rotation, mental rotation, 3D interfaces, virtual environments, motor control, coordination.

INTRODUCTION

Computer input control has traditionally been evaluated using speed (e.g., task completion time) or accuracy (e.g., error rate) as performance measures. As we move to broader topics such as drawing [2], two handed input [8] and high degree-of-freedom (DOF) control, these measures become insufficient to capture the complete quality of input performance.

Driven by the need in 3D user interfaces, much research has been done to evaluate various multiple DOF input devices [see 6, 7, 15, 14 for reviews]. Many fundamental questions on multi-DOF input, however, remain to be scientifically addressed. Can users simultaneously control all 6 degrees of freedom? Or do users actually control fewer degrees of freedom at a time? Can one 6 DOF device be substituted with multiple lower DOF devices? Rice et al [12] observed that controlling 6 DOF with one hand is difficult. Some teleoperation systems, such as the Shuttle Remote Manipulator, also known as the "Canadarm", require two-handed operation: one hand for rotation control and the other for translation control. O'Hara [9] contradicted such an observation and found little performance difference between two 3 DOF controllers and one 6 DOF controller. To answer these questions on a firm scientific ground, we first need to define informative measures beyond speed and accuracy. One of them is the degree of coordination among the multiple degrees of freedom.

COORDINATION MEASURES

For a given trial of motor performance, such as an athlete's movement or a trial of docking in 3D space, people can often agree if it is coordinated. The research challenge here is how to reflect consensual and intuitive understanding by quantitative measures. In the case of multiple degrees of freedom input control, the following measures have been considered as indices of coordination.

Simultaneity. For a task that involves multiple degrees of freedom, coordinated control may require all the degrees of freedom simultaneously activated. Percentage duration that multiple degrees of freedom are co-activated can therefore be a measure of coordination. The drawback of the simultaneity measure is that it does not account for the magnitude of the control actions in each degree of freedom. As long as all of the degrees of freedom are activated, regardless the amount of input generated, the trial is considered coordinated by this measure.

Time-on-target and correlation. In a 3 DOF pursuit tracking task, Ellson [3] recorded *simultaneous* time-on-target (STOT) in all pairs of degrees of freedom as well as all three at once, in addition to TOT (time-on-target) in each of the component dimensions. He then compared STOT scores with the *products* of the component TOT scores. His argument was that if the percent STOT was *equal* to the product of the component TOTs, then the components may be considered independent (uncoordinated). If greater, they were positively correlated (coordinated); if less, negatively correlated (discoordinated). Senders [13] extended Ellson's approach. He computed an approximation of the product-moment correlation coefficient of two separate degrees of freedom as a measure of coordination. Recently, Zhai and Senders [17, 18] extended the time-on-target and correlation measures to 6 DOF tracking tasks and found that subjects tended to have coordinated trials when using a 6 DOF isometric or elastic rate control device. However, both TOT and correlation as coordination measures have drawbacks. One of them is that these two measures do not account for perfect trials. If a trial is 100% simultaneously on target with zero tracking error in all degrees of freedom at all time, the TOT coordination measure will give an uncoordinated result (STOT equals to the product of component TOTs) and correlation become meaningless since errors in all degrees of freedom are zero.

EFFICIENCY AS COORDINATION MEASURE

We propose *efficiency* as a measure of quantifying coordination in multiple degrees of freedom. For a task that involves N degrees of freedom, the trajectory that has the shortest length in that N dimensional space is considered the most coordinated movement. For simplicity, let us examine trajectories on a 2D space, as illustrated in Fig. 1. In order to move from Point A to B in this space, two variables x and y have to be changed from x_A to x_B and y_A to y_B respectively. Supposing we had an input device that has two separate 1 DOF controls, as in an Etch-a-Sketch toy, one possible trajectory would be AC-CB, as a result of moving in the x dimension first and in the y dimension second. In such a case, the two degrees of freedom are completely uncoordinated, because x and y are not moved at the same time, resulting in a longer trajectory than necessary. With an integrated 2 DOF device such as a mouse, one may produce a trajectory *l* that is close to the straight line AB. Trajectory AB is the shortest and most efficient among all possible trajectories. It can also be considered most coordinated in the sense that x and y move simultaneously at the *same relative pace*. Any deviation from the path AB can be considered a result of imperfect coordination, which will result in a longer trajectory. In light of this analysis, we define the translation inefficiency, i.e. the amount of "work wasted", as an inverse measure of translation coordination.

$$\frac{\text{Length of actual path} - \text{Length of shortest path}}{\text{Length of shortest path}} \quad (1)$$

By this definition, trajectory *l* in Fig. 1 is better coordinated than trajectory AD-DB, which is in turn better coordinated than AC-CB.

The same definition of coordination coefficient can be easily generalized to translations in 3D space simply by measuring 3D instead of 2D Euclidean distances. Fig. 2 shows (top curves) an example of the 3D application.

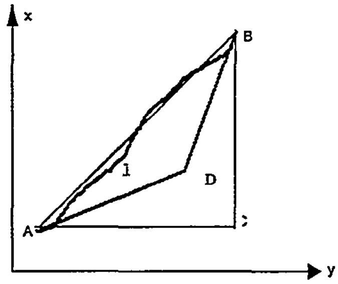

Fig. 1: Coordination with 2 degrees of freedom

To generalize the coordination measure to rotation in 3D space is less straightforward, however. The parameters commonly used in engineering (Euler angles), pitch, yaw, roll, are often misleading [1]. A more valid metric is *rotation vector*. Define the initial mismatch between a cursor and a target (both are 3D objects in 3D space) to be

$$\varnothing_A = \phi_A \mathbf{n}_A = (\phi_{Ax}, \phi_{Ay}, \phi_{Az}) \quad (2)$$

where $\varnothing_A$ is the rotation vector signifying an angle ϕ_A of

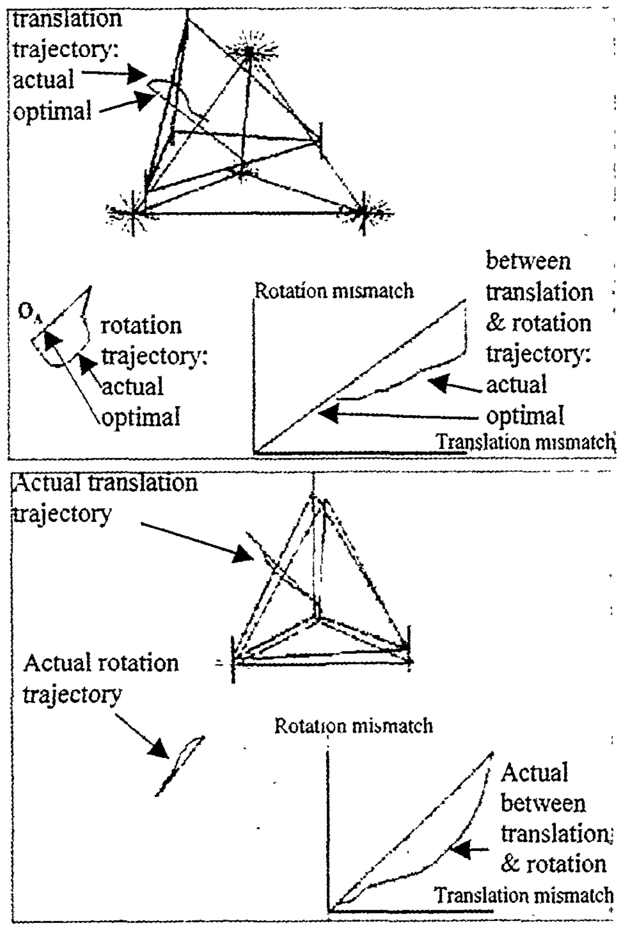

Fig. 2. Coordination measurements superimposed on to a 6DOF docking task. Top: a trial in progress. Bottom: a completed trial. The ratio between actual and optimal trajectory in translation(3D), rotation(3D), and between translation-rotation spaces(2D) quantify the degree of coordination.

rotation about $\mathbf{n}_A$, where $\mathbf{n}_A = (n_x, n_y, n_z)$ is a unit vector defining the axis of the rotation in x, y, z frame of reference, then the *minimum* amount of rotation that the cursor has to go through to reach the target is ϕ_A (Fig. 2). The ratio between ϕ_A and the actual amount of rotation of the cursor upon reaching the target is defined as the rotation coordination coefficient:

$$\frac{\text{Amount of actual rotation - Initial rotation mismatch}}{\text{Amount of actual rotation}} \quad (3)$$

When one can control all 3 rotational degrees of freedom with *perfect* coordination, the rotation mismatch between the cursor and the target will be reduced from $\phi_A \mathbf{n}_A$ to $0\ \mathbf{n}_A$, *without changing the direction of the mismatching rotation vector*. Otherwise, if the 3 rotational degrees of freedom cannot be controlled *simultaneously at the same relative pace*, at an instant of time t the mismatch will be $\phi_t \mathbf{n}_t$ ($\mathbf{n}_t \neq \mathbf{n}_A$), causing a larger amount of actual cursor rotation (Fig. 2, actual trajectory).

The two coordination coefficients defined above deal with translation and rotation separately but do not reveal the coordination aspect between translation and rotation taken together. In other words, a trial can be perfectly coordinated with respect to both its translation trajectory and rotation trajectory, but the rotation and the translation may not necessarily be performed at the same time. Hence, a third coordination factor is defined in the translation-rotation (2D) space which has two dimensions. One is the translation distance, d_t, between the cursor and the target centers of mass, and the other is the rotation mismatch ϕ_t (the magnitude of rotation vector) between the cursor and the target (See Fig. 2). Note that both d_t and ϕ_t are function of time, which define a 2D trajectory over the course of an experiment trial.

Defining coordination by optimality in fact has been proposed in the human motor control literature. For example, Flash and Hogan have measured coordination by the minimum jerk (rate of change of acceleration) for arm movement [4].

COORDINATION IN TWO CLASSES OF 6 DOF INPUT DEVICES: AN EXPERIMENT

Having defined the efficiency measure of coordination, we applied it in two experiments to investigate two 6DOF input devices, the Fingerball and the EGG[1] (Fig. 3).

The Fingerball, similar in shape and size to the 3Ball of Polhemus, represents a class of isotonic (free moving) 6 DOF input devices. Previous study showed that the Fingerball is superior to glove-based devices, due to the fact that one can use both the fingers and the arm/wrist to manipulate the degrees of freedom [16]. The EGG (Elastic General–purpose Grip) represents a different class of 6 DOF devices that are constrained on desktop and work in rate control. In comparison to the commonly used isometric rate controlled desktop device such as the Spaceball™, the EGG offers a slight advantage at the early learning stage due to richer proprioception [15].

(a) (b)

Fig. 3. Two 6 DOF devices used in the experiments. (a) The Fingerball is a free moving, position controlled input device and (b) The EGG is a desktop, elastic rate controlled device. The two experimental devices were based on the same 6 DOF magnetic sensor, Ascension Bird™.

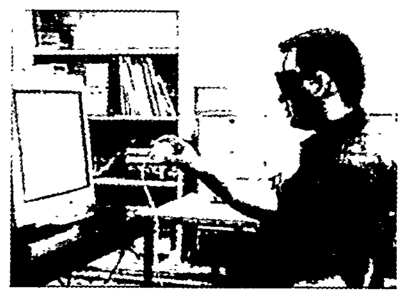

Fig. 4. Experimental Set-up

Experimental Set-up

Experimental Platform and Display

The experiment was conducted with a desktop 3D virtual environment. In order to ensure that the task performance was driven predominantly by differences in input controller conditions rather than by difficulties in perceiving depth information, binocular depth cue was implemented by means of a 120 Hz sequential switching stereoscopic display, together with perspective projection and occlusion (Fig. 2, 4).

Experimental Task

A 6 DOF docking task, illustrated in Fig. 2 and 5, was used for this experiment. (The coordination displays in Fig. 2, superimposed onto the docking task, were not visible to the subjects). In the experiments, subjects were asked to move a 3D cursor as quickly as possible to align it with a 3D target. The cursor and the target were two

[1] The experiments also included an isometric 6 DOF device (the Spaceball™). Due to space limit, this paper only analyzes and reports results with regard to the Fingerball versus the EGG.

tetrahedra of equal size (4.2 cm from the center to each vertex). The edges and vertex markers (bars and spherical stars) of both tetrahedra were colored so that there was only one correct match in orientation. The stars on the target indicated the acceptable error tolerance for each vertex (0.84 cm). During the trial, whenever a corner of the cursor entered into the tolerance volume surrounding the *corresponding* corner of the target, the star on that corner changed its color as an indication of capture. Whenever all four corresponding corners stayed concurrently matched for 0.7 seconds, the trial was deemed completed. At the end of each trial, the trial completion time was printed on the screen. The beginning of each trial was signaled with a long auditory beep and the end of each trial was signaled with a short beep.

At the beginning of each trial, the cursor appeared in the center of the 3D space while the target randomly appeared in one of 8 pre-set locations and orientations. The 8 trials were divided into two sets of 4 trials. In one set of the trials the cursor and the target were mismatched in orientation about axes that were parallel with the viewer's primary coordinates (X, Y, Z). In another set the orientation mismatches were about arbitrary vectors that did not coincide with the X, Y, Z coordinates. Recent research in mental rotation [10] has shown that humans cannot effectively perform mental rotation about arbitrary 3D axes. We hypothesized that once interaction (manipulation) is allowed, subjects should be able to find the correct rotation path. Note that the magnitude of mismatch of both translation and rotation in each trial in one set correspond to a trial in the other set, so the total amount of translation and rotation are equalized in the two groups.

Experimental Design

Both experiments used between-subject design in order to avoid asymmetrical skill transfer between devices [11]. In Experiment 1, each device group had 16 subjects, none of them had prior experience with using 6 DOF input devices.

Each experiment had 5 repeated tests, which consisted of randomly shuffled 8 trials (with initial locations and orientations as described earlier). Test 1 started after a short demonstration and two warm-up trials. Test 2, Test 3, Test 4, and Test 5 started 10, 20, 30, and 40 minutes after the beginning of Test 1 respectively. Practice trials (with completely random initial locations and orientation) were given between the tests. The entire experiment lasted about 1 hour for each subject.

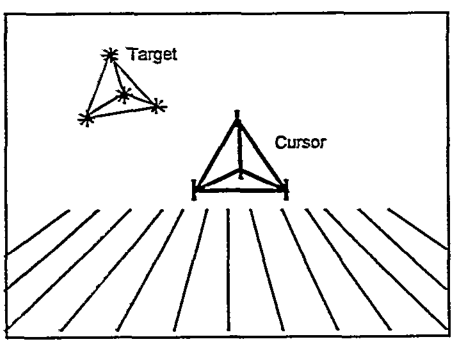

Fig. 5. 6 DOF Docking Task

A follow-up experiment, Experiment 2, was conducted for two reasons. First, we wanted to see effect of retention and extended practice. Second and more importantly, we wanted to know if a coordination difference between the two devices still exists if we give explicit instructions emphasizing coordination.

16 subjects (8 in each device group) who participated in Experiment 1 were called back two months later in Experiment 2, which started with the same instruction as in Experiment 1. After regaining their skills in Test 1 and Test 2, subjects were instructed (through demonstration and explanation) to perform the trials as coordinated (producing smooth and short trajectory) as possible, while trying to complete each trial as quickly as possible.

As a motivating tactic, before Test 3 of Experiment 2, completion times were displayed to the subjects after each trial and each test. After Test 2 of Experiment 2, these were displayed together with coordination measures.

Experimental Results and Discussion

The results of statistical analyses of data collected in the two experiments are summarized in Table 1.

Completion time. As shown in Fig. 6, for both experiments, the mean trial completion time of the free position control (Fingerball) group was significantly shorter than that of the elastic rate control (EGG) group. (Due to space constraint, all F-test degrees of freedom and significance level are summarized in Table 1).

Particularly worth noting is that after Test 2 in Experiment 2 when the emphasis on coordination was given, the subjects sacrificed their completion time in order to make more coordinated movements (Test 3). As they gained more practice, however, the completion time continued to improve.

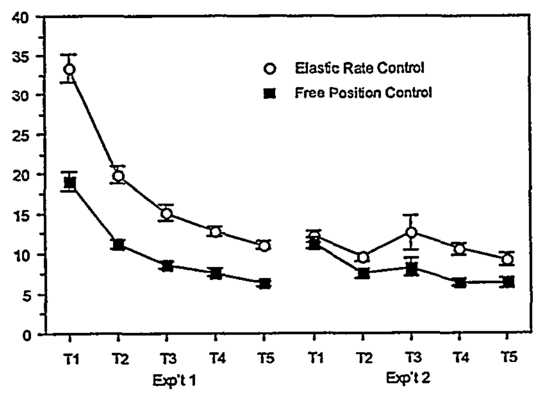

Fig. 6. Mean trial completion time with standard error bars

Table 1: Summary of Experiment 1 Variance Analyses

	Independent variable	Device		Exp't Phase		Device X Phase		Rotation Type		RType X Device	
		$F_{1,30}$	P <	$F_{4,120}$	P <	$F_{4,120}$	P <	$F_{1,30}$	P <	$F_{1,30}$	P <
Exp't 1	Completion Time	30.8	.0001	232.8	.0001	.116	.97 *NS*	27.6	.0001	.96	.33 *NS*
	Translation Inefficiency	44.4	.0001	56.4	.0001	1.7	.15 *NS*	35.1	.0001	.26	.61 *NS*
	Rotation Inefficiency	24.7	.0001	68.2	.0001	.197	.93 *NS*	58.0	.0001	16.2	.001
	Between Tran & Rot	18.0	.0005	94.5	.0001	1.20	.32 *NS*	13.1	.005	.308	.58 *NS*
	Total Transport	18.7	.0005	83.2	.0001	1.78	.14 *NS*	39.4	.0001	.772	.39 *NS*
		$F_{1,14}$	P <	$F_{4,56}$	P <	$F_{4,56}$	P <	$F_{1,14}$	P <	$F_{1,14}$	P <
Expt 2	Completion Time	5.31	.05	13.8	.0001	2.54	.06 *NS*	26.8	.0001	14.3	.005
	Translation Inefficiency	36.3	.0001	42.7	.0001	1.30	.27 *NS*	3.99	.07 *NS*	3.17	.10 *NS*
	Rotation Inefficiency	27.1	.0001	33.5	.0001	2.84	.05	40.8	.0001	38.2	.0001
	Between Tran & Rot	14.7	.005	5.58	.0001	4.42	.05	2.18	.16 *NS*	6.72	.05
	Total Transport	22.7	.0005	54.2	.0001	2.82	.05	24.8	.0005	13.9	.005

Translation. Fig. 7 illustrates the mean translation inefficiency measured in the experiments. In contrast to the trial completion time data, for both experiments, the free moving position control device was significantly (Table 1) less efficient than the elastic rate control device.

Subjects significantly improved their translation coordination over the five tests in each experiment, particularly after Test 2 of Experiment 2 when emphasis on coordination and efficiency was given. In terms of magnitude, on average the initial translation trajectories were 300% (free position control group) or 200% (elastic rate control group) longer than the optimal path. At the end of Experiment 2, the mean inefficiency of the elastic rate control group was reduced to 43.3% but that of the free position control group was still at 88.7%.

The lesser degree of coordination of the free moving position control device is plausible. First, position control is directly proportional to hand/finger movement and thus constrained to anatomical limitations: joints can only rotate to certain angle. In contrast, with an elastic rate control device, a small amount of hand movement is mapped onto the velocity of the cursor movement. The integral transformation (from velocity to cursor position) in rate control makes the actual cursor movement a step removed from the hand anatomy.

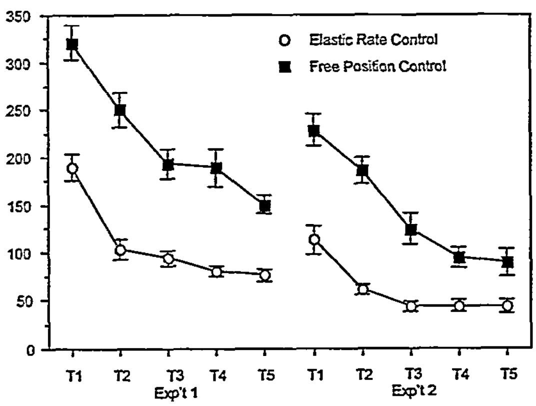

Fig. 7. Mean translation inefficiency (%)

Secondly, the integral transformation in rate control is a low pass filter that removes the higher frequency noise, producing smoother trajectories than position control. This also contributes to the higher efficiency of rate control.

Rotation. Fig. 8 illustrates the mean rotation inefficiency of the two devices. Similar to translation inefficiency, for both experiments, the rotational inefficiency with the free position control device was significantly higher than with the elastic rate control device (Table 1). Subjects also significantly improved their rotation performance over the five tests in each experiment. At the end of Experiment 2, the mean rotation inefficiency of the free position group was reduced to 97.3% and elastic rate control group reduced to 70.4%.

Note that subjects' rotation inefficiency was much higher than that of translation, up to 580% in Test 1 of Experiment 1 by the free position control group. One possible reason is that humans can not effectively do mental rotation of 3D objects. In other words, subject might not be able to figure out the ideal rotation axis before they manually trying out the movement. We will return to this issue shortly.

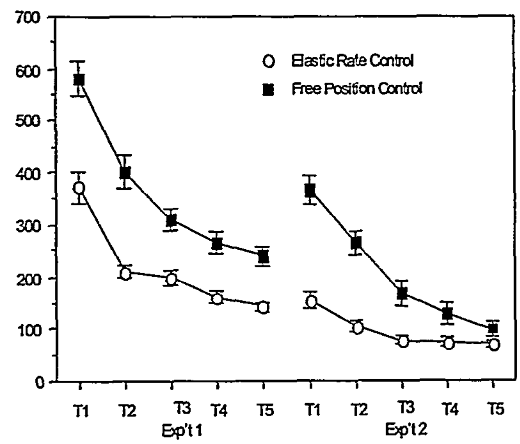

Fig. 8. Mean Rotation Inefficiency (%)

Between translation and rotation. As shown in Fig. 9, the trend in subjects' coordination between total translation and total rotation was similar to that of translation or rotation. The rate control group was significantly more efficient than the position control group in *both* experiments, although the magnitude of the difference was reduced after the instruction change during Experiment 2. At the last test, the inefficiency of the rate and position control group was 26.7% and 36.8% respectively. Interestingly, the mean percentages of "wasted" movement in the translation-rotation space were in fact lesser than in the translational space and rotational space, suggesting that there is little reason to separate translation and rotation control into two hands, as in some telerobotic systems.

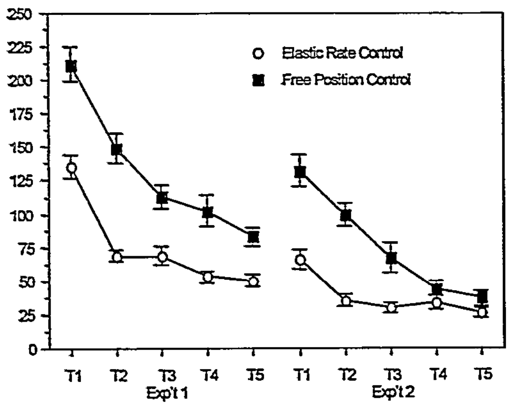

Fig. 9. Inefficiency in translation-rotation space

Total Transport. The above three measures separately indicated users' efficiency with the two 6 DOF input devices in translation, rotation, and between translation and rotation. The total transport, defined as the line integral of the four vertices of the cursor tetrahedron, was used as an integrated measure of coordination in 6 degrees of freedom. Same as the conclusions drawn from the previous three measures, the rate control device was significantly more efficient (or more coordinated) than the position control device. Practice and instructional emphasis improved efficiency with both devices and the difference between the two was reduced by the instruction, but the final difference was still significant. At the last test of the Experiment 2, the inefficiency of the rate control group was 65.4% and that of the position control group was 96%.

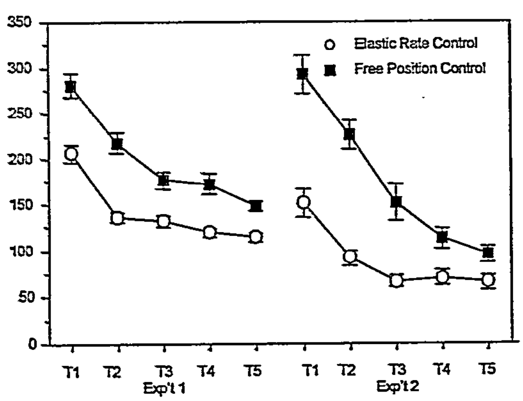

Fig. 10. Inefficiency in total transport

The impact of 3D mental rotation. As recent studies in mental rotation have shown [10], human subjects are incapable of mentally rotating objects in *3D* space. This is particularly true when the rotation axis does not coincide with viewer's primary axes. In Parson's experiments, subjects did not perform better than chance in mentally finding the correct rotations about arbitrary 3D axes. In our experiments, it is indeed true that the subjects were significantly less efficient in trials with arbitrary initial rotation mismatch than in trials with rotation mismatch about primary axes. Fig. 11 shows such an impact.

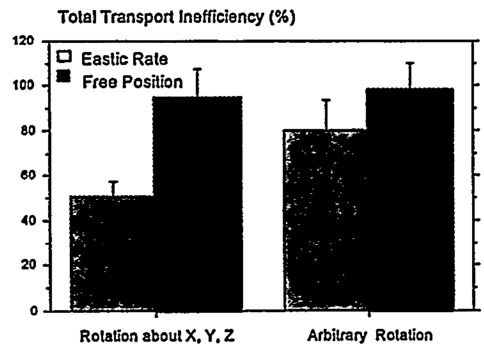

Fig. 11. The impact of rotation type on total movement

(total transport data from the last test of Experiment 2)

In not a single trial in our experiments, however, were the subjects unable to successfully complete a trial both in translation and in rotation, including trials in practice sessions when the rotation mismatches are randomly generated and not repeated. The reason, in our view, lies in interaction, the interaction between action and cognition. Note that to be able to manipulate still needs the involvement of mental rotation, the probability to match the target by random manual exploration could not be high. We should point out that the focus of this study is not on mental rotation, although interesting research can be carried in such a direction with the current paradigm.

A greater efficiency difference between the two devices was found when the trials involved rotations only about viewer's primary axes. This is again plausible: for arbitrary rotation trials, the rotation inefficiency was partially caused by physically searching the correct rotations. For trials that were mismatched about the primary rotation axes, subjects can mentally find the correct rotation more easily so the advantage of the rate control device that may enable higher degree of coordination was better revealed in such trials.

CONCLUSIONS AND GENERAL DISCUSSIONS

The efficiency based coordination measure

Although the experiment showed that the efficiency based measure of coordination was sensitive enough to reveal performance differences, this is not necessary the only "correct" measure to quantify coordination in multiple degrees of freedom. One possible argument against such a measure is that it is a *definition,* not a validated conclusion about coordination. The critical issues are whether it is an arbitrary definition or a definition in agreement with our common sense judgement of coordination, and furthermore, if the definition is informative. We think both are true. Another drawback of the efficiency measure is that other factors besides manual coordination, such as the mental rotation factor presented above also contribute to the trajectory efficiency, although one can argue that coordination simply includes a cognitive component.

The coordination measure proposed in the paper can be applied to research beyond 6 DOF input devices. For instance, it is conceivable to define coordination of human movement (such as arm movement) that involves N joints. If we defined N dimensional coordination space with each axis as the distance from the angular position of a joint to its goal position, then a perfectly coordinated movement should result in a straight line from the initial mismatch to (0, 0, ...0) in that space. Similarly, we can also define coordination for two-handed computer input.

Isomorphic manipulation vs. tool operation

By applying the efficiency based coordination measure to input device evaluation, we begin to gain insights into the characteristics of 6 DOF input devices that have not been rigorously demonstrated before. Our experiments showed that while the 6 DOF free moving position control device was faster in docking task completion, the elastic rate control device produced more efficient or coordinated trajectories. The difference was true even after emphasis on coordination was explicitly given to the subjects. The contrast between the pros and cons of the two types of devices tested illustrate a more general philosophical issue on computer input device design: isomorphism (direct manipulation) versus tool-using that has been informally debated by researchers [5]. As shown in Fig. 12, there is in fact a continuum on the dimension of directness[2]. The most dominating factor to directness of an input method is the transformation from the *control space* to *display space.* The more mathematically complex this transformation is, the more indirect the input technique is. Input techniques with first order (rate control) or higher order control dynamics are indirect "tools". With these techniques, one or more integrals are involved in the mathematical mapping from the control space (user's control actions) to the display space (cursor movements). The elastic rate controller (EGG) used in the experiments is such an example.

Moving to the left of Fig. 12, input devices become more direct. For position control techniques, the mathematical transformation from the control space to the display space is a multiplication, which is simpler than integration. Among position control techniques, *absolute* devices, such as a 2 DOF digitizing tablet or the 6 DOF Fingerball in Experiment 4 are more direct than *relative* devices, such as a 2 DOF mouse or the 6 DOF glove [16]. Relative devices require a clutch mechanism to engage and disengage the link between control actions and cursor movements. For a mouse, for example, lifting it from mouse pad will disengage the linkage between control and display.

← Directness Indirectness →

Isomorphism Tools

Transformation	position control			Rate control	Higher order control
	Absolute		Relative (Clutch)		
	C/D Isospace	C/D off-set			
2DOF Examples	Touch Screen	Tablet	Mouse	Joystick	
6 DOF Examples		Fingerball	Glove	Egg Spaceball	

Fig. 12. Isomorphism - tool continuum: A taxonomy of classifying input devices according to directness of transformation from control space to display space

Another factor that affects the directness of position control techniques is the control-display (C-D) ratio. When the C-D ratio is 1, the multiplication operation is reduced to an assignment (copying) operation, which makes the input control more direct than when the C-D ratio is not 1.

There is still another factor that makes some absolute position input techniques more direct than the others: the orientation or location *offset* between the control space and the display space. Both a touch-screen and a tablet are absolute position control devices but the latter has an offset between the display and the control space in orientation (about 90° in pitch) and in location (about 20 - 40 cm in the vertical and/or in the horizontal axes). A touch screen interface is therefore more direct than a tablet interface. In the experiments presented in this paper, all input techniques had a translation offset between the control space and the display space, but no orientation offset. 6DOF techniques without offset can conceivably be implemented, particularly in immersive virtual environments in which the display space (where the user looks) and the control space (where the user moves her limbs) can completely overlap with each other.

It should be noted that to the left of Fig. 12 there are input devices that are even more direct. These are the position control devices with force-reflecting capabilities. The

[2] Fig. 12 can be viewed as an input device design space or taxonomy. For proposals and discussions of input taxonomy, see W. Buxton "Lexical and Pragmatic Considerations of Input Structure" *Computer Graphics* 17 (1); J. Mackinlay, S.K. Card, G.G. Robertson "A Semantic Analysis of the Design Space of Input Devices" *Human-Computer Interaction vol 5* pp145-190.

ultimate isomorphic input controller is one that allows force feedback in all directions, to recreate what we would feel when manipulating real 3D objects directly with our bare hands. In other words, the ultimate isomorphic interfaces are completely "transparent" to the user.

It is important to note that there are both advantages and disadvantages to techniques on each end of the isomorphism - tool continuum, as illustrated by our coordination experiments. In daily life, we prefer to perform many tasks with our bare hands. Even with a glove, the small "transformation" between the hand and the actual manipulation may be undesirable on some occasions. On the other hand, we do frequently use various tools, sometimes as simple as rulers, wrenches, screwdrivers, etc., for precision, for power and for overcoming some of our other physical limitations. In general, more isomorphic (more direct) designs are more intuitive and require less learning. Such devices are needed for applications where an explicit learning period is perhaps not available, such as commercial video games where users should be able to walk-up and play immediately. The disadvantages with such isomorphic designs lie in possible fatigue, coarseness of the control action, and anatomical limitations of the human limb. In contrast, less direct, tool-like devices may take more time to learn but may be more efficient in terms of reduced fatigue, coordinated motions, and fewer physical limitations of the human limb. Such designs can be more suitable for tasks of long duration, such as in teleoperation and image visualization.

ACKNOWLEDGEMENTS

The experiments presented here were conducted at the ETC lab of the University of Toronto. The study was made possible by a research grant from ITRC, a center of excellence of Ontario. We thank our co-grantee Bill Buxton for his support and close collaboration. We also like to thank the IBM Almaden Research Center for supporting the first author to continue and complete this study.

REFERENCES

1. Altmann, S. L. (1986). *Rotations, Quaternions, and Double Groups*. Oxford: Clarendon Press.
2. Accot, J. and Zhai, S., Beyond Fitts' Law: Models for trajectory-based HCI tasks, *Proc. CHI'97*, 295-302.
3. Ellson, D. C. (1947). *The independence of tracking in two and three dimensions with the B-29 pedestal sight*. Report TSEAA-694-2G, Aero Medical Laboratory.
4. Flash, T., Hogan, N. The coordination of arm movements: An experimental confirmed mathematical model, *The Journal of Neuroscience*, Vol 5, No. 7. 1688-1703, 1985.
5. Green, M., Bryson, S., Poston, T. & Wexeblat, A, Hands off my VR: the role of gestures in VR (panel session). *Proc. of Virtual Reality Software and Technology (VRST 1994)*, 267-268.
6. Hinckley, K., Tulio, J., Pausch, R., Proffitt, D, Kassell, N., Usability Analysis of 3D Rotation Techniques, to appear *Proc. of ACM Symp. UIST'97*, 1997.
7. Jacobus, H. N., Riggs, A. J., Jacobus, C. J., & Weinstein, Y. (1992). Implementation issues for telerobotic handcontrollers: human-robot ergonomics. In M. Rahimi & W. Karwowski (Eds.), *Human-Robot Interaction*. London: Taylor & Francis.
8. Kabbash, P., Buxton, W., Sellen, A., Two-handed input in a compound task, *Proc. CHI'94*, 417-423.
9. O'Hara, J. (1987). Telerobotic control of a dexterous manipulator using master and six-DOF hand controllers for space assembly and servicing tasks. *Proc. Human Factors Society 31st Annual Meeting*.
10. Parsons, L., Inability to reason about an object's orientation using an axis and angle of rotation. *Journal of Experimental Psychology: Human Perception and Performance*, 1995, Vol.21, No.6, 1259-1277.
11. Poulton, E.C., Unwanted asymmetrical skill transfer effects with balanced experimental designs. *Psychological Bulletin, 66* 1 (1966), 1-8.
12. Rice, J. R., Yorchak, J. P., & Hartley, C. S. (1986). *Capture of satellites having rotational motion. Proc. Human Factors Society 30th Annual Meeting*
13. Senders, J. W., Christensen, J. M., & Sabeh, R. (1955). *Comparison of single operator's performance with team performance in a tracking task* (TN-55-362): Aero Medical Laboratory, Wright Air Development Center.
14. Ware, C. Using hand position for virtual object placement, *the Visual Computer*, 1990, Vol 6, 245-253
15. Zhai, S. (1995). *Human Performance in Six Degree of Freedom Input Control.* Ph.D. Thesis, Univ. of Toronto. Http://vered.rose.toronto.edu/people/shumin.html
16. Zhai, S., Milgram, P. Buxton, W., The influence of muscle groups on performance of multiple degree of freedom input control, *Proc. of CHI'96*.
17. Zhai, S., Senders, J.W., Investigating Coordination in Multidegree of Freedom Control I: Time-on-Target Analysis of 6 DOF Tracking, to appear in *Proc. Human Factor Ergonomics Society* 1997.
18. Zhai, S., Senders, J.W., Investigating Coordination in Multidegree of Freedom Control II: Correlation Analysis of 6 DOF Tracking. *ibid*